EVALUATION OF PEDO-TRANSFER FUNCTIONS FOR THE ESTIMATION OF HYDRAULIC PROPERTIES IN SOME MOROGORO SOILS, TANZANIA

BY

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A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN AGRICULTURAL ENGINEERING OF SOKOINE UNIVERSITY OF AGRICULTURE

2002

ABSTRACT

A study was conducted to evaluate some selected pedotransfer functions (PTFs) for soil water retention (SWR) and saturated hydraulic conductivity (K_s) using soils from Sokoine University of Agriculture (SUA) farm. Laboratory methods were used in analysis of collected samples for soil texture, organic carbon (OC), bulk density (BD), total porosity (p) and SWR characteristics (soil WRC). The K_s values were determined using the double ring and tension infiltrometer methods. Existing PTFs for soil WRC and K_s were selected from the literature for evaluation depending on their usability from the obtained soil data, easiness to apply them and their predictive capacity. Representative soil physical properties (RSPPs) for each soil profile studied were calculated using the ratios of individual soil profile horizons depths divided by the total depth of the soil profile. The RSPPs were used in evaluating PTFs for K_s estimation based on field measured K_s. The pedotransfer functions of Tomasella and Hodnett (1998), and PTFs of Ahuja *et al.* (1984), Campbell (1985), Vereecken, *et al.* (1990) and Jabro (1992) for SWR and or K_s were evaluated using obtained soil physical properties. Good estimates of SWR were obtained by Tomasella and Hodnett (1998) PTFs. Estimates of K_s proved unreliable by the evaluated PTFs. Simple linear multiple regression models were developed for SWR and K_s using determined soil physical properties following similar procedures to the evaluated PTFs. This was done for SWR so as to include important soil physical properties such as BD and OC, which were not included in evaluated PTFs. Soil texture, BD and OC contributed significantly ($p < 0.05$) to the developed regression equations for

SWR characteristics at different matric potentials. Retained soil water contents significantly ($p < 0.05$) correlated to percentage clay, OC and BD in most developed regression equations. Estimates of AWC by the developed regression equation were not good enough compared to other estimated soil WRC. Only representative percentage clay had a significant ($p < 0.05$) contribution to the developed regression equation for K_s estimation. The correlation coefficient for the developed regression equation was high ($r = 0.94$). Generally, the K_s values estimated using the developed models matched measured values well with mean differences not significantly different from zero. The root of mean squared differences between measured and estimated SWR and K_s were 0.055 cm^3cm^{-3} and 0.198 mm/h respectively. The developed PTFs for soil WRC and K_s gave good estimates compared to evaluated PTFs. It is recommended that more PTFs for soil hydraulic properties be developed using large soil samples under variable soil conditions for reliable estimations of the properties.

DECLARATION

I, Makarius Victor Chogimembe Mdemu do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my original work and that it has not been submitted for degree award in any other University.

Signature MMdemu...........................

Date 06.5.02...........................

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ACKNOWLEDGEMENTS

May the almighty Lord be praised for allowing me put the final touches in this work. Sincere thanks to my supervisors Dr. M.K. Mulengera of the Department of Agricultural Engineering and Land Planning and Dr. P.W. Mtakwa of the Department of Soil Science for their valuable guidance, constructive criticism and ideas in the whole period of my research and dissertation write up. Truly the point reached by this work is a result of their moral and material support provided to me during the research work and dissertation write up.

I am grateful for the scholarship through SACCAR/GTZ that afforded me an opportunity to study at SUA. Doctor. A.K.P.R. Tarimo is highly acknowledged for the keen co-ordination of the scholarship in the Department of Agricultural Engineering and Land Planning.

Thanks are also due to Prof. N. Hatibu for his encouragement during the write up of this work, Mr. Y.H. Matembo, Laboratory Technician who responded whenever he was requested for assistance, my field work assistant, Mr. A. Abedinego and all the members of the Department of Agricultural Engineering for their cooperation during the entire period of this study. The companionship of my fellow classmates meant a lot and I am thankful to them all.

Lastly thanks to my wife Immakulata and my son William for accepting the loneliness at all times I was not at home and for their encouragement during the period of study.

DEDICATION

This dissertation is dedicated to the memory of my beloved father, Victor Chogimembe Mdemu whose silent presence has guided my effort.

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LIST OF ABBREVIATIONS AND SYMBOLS

AWC	Available soil water capacity
BD	Bulk density
CEC	Cation exchange capacity
CV	Coefficient of variation
DR	Double ring infiltrometer
Eq.	Equation
FAO	Food and Agriculture Organization of United Nations
FC	Field capacity
Fig.	Figure
GDS	Geometrical standard deviation
GMPS	Geometric mean particle size distribution
GSDER	Geometrical standard deviation of the error ratio
HC	Hydraulic conductivity
K_s	Saturated hydraulic conductivity
MD	Mean difference
MR	Moisture retention
MRC	Moisture retention characteristics
MSE	Mean of square errors
ND	Not determined
OC	Organic carbon
PTFs	Pedotransfer functions
PWP	Permanent wilting point

R	Correlation coefficient
RBD	Representative soil bulk density
RMSD	Root of mean squared difference
RMSE	Root of mean square errors
ROC	Representative organic carbon
RP	Representative total porosity
RPSD	Representative particle size distribution
RSPPs	Representative soil physical properties
RTC	Representative texture class
SFP	SUA farm profile
SHC	Soil hydraulic conductivity
SMR	Soil moisture retention
SS	Specific surface area
SSE	Sum of square errors
STDEV	Standard deviation
SUA	Sokoine University of Agriculture
SWR	Soil water retention
TI	Tension infiltrometer
UNCEL	University of NewCastle Environmental Laboratory
USA	United States of America
USDA	United States Department of Agriculture
WRC	Water retention characteristics

CHAPTER ONE

1. INTRODUCTION

Soil hydraulic conductivity and soil water holding capacity are key soil parameters in soil and water management practices for sustainable and improved agricultural production. Tietje and Hennings (1996) point out that these parameters are increasingly needed but they are not routinely determined by soil surveyors.

Soil hydraulic conductivity and soil water holding capacity are important for both modeling the hydrology of segments of the landscape and for evaluating field soil water regimes in relation to the potential of soil for various uses (Bouma, 1981). The saturated hydraulic conductivity of some or all soil horizons is related to the hazard of ponding, runoff and erosion and to the potential of a soil for tile drainage, septic filter fields, production of certain crops and other uses. Saturated hydraulic conductivity is an important parameter used in determining infiltration, irrigation practice, drainage design, runoff, ground water recharge and in simulating leaching and other agricultural and hydrological processes (Jabro, 1992). Application of soil water flow theory to many practical problems requires estimates or measurements of hydraulic conductivity for unsaturated soil over the water contents range of interest. Knowledge of unsaturated hydraulic conductivity is one of the prerequisites in describing water flow and solute transport in soils (Vereecken, 1995; Vereecken *et al.*, 1997), determining crop production potential and leaching of agrochemicals (Van den Berg *et al.*, 1997).

It is not practically possible to directly determine the saturated and unsaturated hydraulic conductivity values of horizons of all soils, thus, estimates are necessary (McKeague *et al.*, 1982). Further more, even with improved equipment direct measurements of soil hydraulic conductivity and soil water holding capacity are expensive, time consuming and labour intensive. These soil parameters alternatively have to be estimated using available soil data such as particle size distribution, organic matter content, bulk density and soil porosity (McKeague *et al.*, 1982; Jabro, 1992; Tietje and Hennings, 1993; 1996; Gowing and Young, 1996; Schaap *et al.*, 1999; Young *et al.*, 1999).

The methods or equations used to estimate soil hydraulic conductivity and / or water holding capacity from available soil data are called pedo-transfer functions (PTFs) (Gowing and Young, 1996; Tietje and Hennings, 1996; Young *et al.*, 1999). Pedotransfer functions are regression equations that either directly or indirectly relate readily available, easily measured soil physical and chemical data to soil hydraulic properties. They serve to translate the basic information found in the soil survey into a form useful in broader applications, such as simulation modelling (Wagenet *et al.*, 1991).

Climate, organisms and relief are some of the soil forming factors that vary worldwide from one region to another. As a result, the soils formed in such regions differ in terms of depth, physical, biological and chemical properties. Such soil variations are quite significant (FAO, 1990).

The major work in the development of PTFs has been in the USA and Europe and therefore the soils used have been American or European (Young *et al.*, 1999). Variations in soil physical, biological and chemical properties, which are the key parameters for PTFs, between the tropical and temperate soils cause direct inapplicability of the existing pedo-transfer functions to other areas such as Sub-Saharan Africa (Gowing and Young, 1996, Young *et al.*, 1999).

Several PTFs are now available for use to estimate soil hydraulic conductivity and soil water holding capacity (King and Franzmeir, 1981; Tietje and Hennings, 1993; 1996; Gowing and Young, 1996; Schaap *et al.*, 1999). Tietje and Tapkenhinrichs (1993) and Schaap and Leij (1998) are among many researchers who have carried out studies concerning applicability of PTFs (Schaap *et al.*, 1999).

There has been on-going work in a number of locations in Tanzania involving research teams from the University of Newcastle upon Tyne in the UK and Sokoine University of Agriculture that are attempting to evaluate the ability of PTFs to accurately predict soil hydraulic properties (Young *et al.*, 1999). Also Mzirai (1997) studied parameter optimization for the van Genuchten (1980) PTFs for Itogolo (*Dystric Eutric Regosols*) soils of Sukuma Catena.

Very little research has been conducted to develop or modify PTFs that are applicable in Sub-Saharan Africa. This hinders direct field application of the PTFs to these areas where the soil forming factors are different from those where the models were developed.

Pedotransfer functions are very important in estimation of soil hydraulic properties, which are a prerequisite in soil and water management practices for sustainable agricultural production. Considering that little work has been done in Tanzania in estimation of these properties, there is a need to evaluate and possibly modify the PTFs to make them suitable for intended purposes in the specific areas of application. It is for this reason that this study was initiated.

The general objective was to adopt some promising PTFs for their use on soils found in SUA farm, Morogoro. The specific objectives were:

(i) to identify from the literature some PTFs to be evaluated;

(ii) to carry out statistical regression analysis of the measured soil physical, chemical and biological properties vis-a-vis measured hydraulic properties and soil water holding capacities to come up with modified PTFs.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Soil Hydraulic Properties

The rate of movement of water through the soil is of considerable importance in many aspects of agricultural and urban life. The entry of water into soil, the movement of soil water to plant roots, the flow of water to drains and wells, and the evaporation of water from the soil surface are but a few of the obvious occasions in which the rate of movement plays an important role (Klute and Dirksen, 1986). The soil properties that determine the behaviour of soil water flow systems are the hydraulic conductivity and water retention characteristics. These properties which determine the response of soil water systems to imposed boundary conditions are often called the hydraulic properties of the soil (Klute and Dirksen, 1986). Soil hydraulic properties determine the rate of movement of water into the soil including, among others, infiltration, evaporation and drainage. Soil water retention characteristic (WRC) and the hydraulic conductivity (HC) are the properties used to describe the hydraulic properties or the hydraulic behaviour of the soil (Mzirai, 1997). Theoretical description of hydraulic behaviour is difficult due to the complexity of the pore geometry and the interaction between soil hydraulic behaviour needed in quantitative description of soil water system.

2.1.1 Soil water retention characteristics

The relationship between the soil water content and the soil water suction is fundamental to the characterization of the hydraulic properties of a soil (Klute, 1986). The relationship is identified in the literature by various names including water retention function, moisture characteristics and a capillary pressure-saturation curve (Klute, 1986). The water retention function is primarily dependent upon the texture or particle size distribution of the soil, the structure or arrangement of the particles, bulk density, organic matter content and other soil properties. According to Mzirai (1997) other factors affecting soil WRC are those which have influence on soil physical properties. For example, soil properties are invariably altered by land use such as tillage and land fallow. It was observed by Makungu (1991) and Mwendera (1992) that tillage increased moisture content held at 0.1 kPa (pF 0.0) and reduced moisture content held at 10 kPa (pF 2.0). The increase of moisture content was highest in rolled soil as compared to harrowed soil. Researchers, among them being Arya and Paris (1981), Brakensiek *et al.* (1982), Saxton *et al.* (1986) and Vereecken *et al.* (1989) have established different relationships between soil water retention characteristics to soil physical properties.

2.1.2 Soil hydraulic conductivity

Soil hydraulic conductivity, K, is the volume of water which will pass through a unit cross-sectional area of a soil in unit time, given a unit difference in water potentials (cm/h; mm/h; m/d) (Landon, 1991). Soil hydraulic conductivity data are of use in analysis of any soil-water flow system. These include drainage if soil is used for agricultural as well as for engineering purposes, irrigation design and seepage below dams. The fact that hydraulic conductivity appears as a proportionality factor in Darcy's law does not necessarily mean that it is or must be constant (Klute, 1986). Soil hydraulic conductivity is influenced by various chemical, physical and biological processes that take place in the soil. Soil water content, porosity, texture and structure are among the physical factors affecting soil hydraulic conductivity (Childyal and Tripathi, 1995, Mzirai, 1997). Other factors affecting SHC, according to Bouwer (1978), are temperature, ionic composition of the water, the presence of entrapped air and soil matric potential.

2.2 Determination of Soil Hydraulic Properties

Choice of the method for determining soil hydraulic properties depends on such factors as the available equipment, nature of the soil, the kind of samples required, skills and knowledge of the experimenter and the purpose for which the measurements are being made (Klute and Dirksen, 1986). Measurement techniques can be divided into direct measurement methods and inverse or indirect methods.

Estimation of soil hydraulic properties from easily measurable soil properties such as texture is referred to as the indirect or inverse methods in this work. Direct measurement methods require the experimenter to obtain one to several steady–state measurements using restrictive initial boundary conditions. *In situ* direct methods such as the instantaneous profile technique (Watson, 1966) are generally favoured over laboratory tests based on small samples (Jaynes and Tayler, 1980). Data obtained by *in situ* instrumentation are therefore, used as the standard against which comparisons are made from results of methods that are less costly and laborious (Marion *et al*., 1994). Significant errors due to soil heterogeneity are the main set back of *in situ* direct measurement methods. The advantage of direct measurement methods is that no *apriori* choice has to be made concerning the functional relationship between the variables such as pressure head, moisture content, and hydraulic conductivity.

Indirect measurement methods for soil hydraulic properties estimate parameter values of functions relating moisture content with matric potential or hydraulic conductivity with matric potential, or both and require prior choice of the function type (Marion *et al.*, 1994). Therefore, under indirect methods rather than measuring the quantity of interest directly, auxiliary variables are determined in experimental set up under controlled initial boundary conditions (Vereecken *et al.*, 1997). In the next sections direct methods for determination of soil moisture retention and soil hydraulic conductivity are reviewed. Laboratory and field methods exist for both saturated and unsaturated soil hydraulic conductivity and soil moisture retention. The main concern of this work was the estimation of soil moisture retention and saturated soil hydraulic conductivity. The laboratory and field methods for determining unsaturated soil hydraulic conductivity are briefly reviewed to explore opportunities, which are frequently used in determination of these important soil hydraulic properties. Although field methods for determination of soil moisture retention are considered the best compared to laboratory ones, materials and time constraints necessitate use of laboratory methods. Saturated hydraulic conductivity was determined using field methods in this study.

2.2.1 Direct determination of soil water retention characteristics:

Laboratory methods for soil water retention characteristic determination

The determination of the soil water retention characteristics (WRC) is mostly done through laboratory measurements. In the laboratory soil WRC is determined through equilibration of saturated soil samples (disturbed or undisturbed) with a saturated porous medium on which a negative or positive pressure is applied (Vereecken, 1988). The negative pressure is applied by means of a hanging water column or pump (suction cell apparatus). For water contents at higher log-transformed matric potential (pF) values, the sample is equilibrated on a ceramic plate in a pressure plate apparatus by the application of a positive pressure (Vereecken, 1988). At equilibrium the volumetric water content (θ) of soil is determined and paired with the value of soil water pressure head (h).

When the suction cell apparatus is used, the wet soil sample is in hydraulic contact with the bulk water through a porous plate. Atmospheric pressure is applied to the soil and the pressure in the bulk-water is reduced to sub-atmospheric levels, thereby reducing its hydraulic head. Water flows out of the sample until hydraulic equilibrium is reached. The water content and the matric pressure head at equilibrium are then determined (Klute, 1986). When the wet soil sample is placed on a wetted porous plate in a pressure cell and gas phase pressure in the cell is raised above atmospheric, the hydraulic head of the soil water is increased and water flows out of the sample through the porous plate. As the soil drains the matric component (h_m) of the pressure head and the hydraulic head of the water in the sample decrease.

Eventually hydraulic equilibrium is established between the soil water and the water in the reference system (Klute, 1986).

The laboratory determinations of soil water retention are categorized into low range, medium range and high range systems. The low range system is suited to measurements in the matric pressure head range of zero to approximately 20 kPa of water. The mid-range system is suited to measurements in the matric pressure head range of 20 to 100 kPa of water and the high range system at matric pressure head of 100 to 1500 kPa (Klute, 1986). Soil loss and disturbed samples during transfer of equilibrated wet samples and fluctuation of the regulated cell pressure are among the setbacks of the laboratory methods for water retention. Equilibration time may not be the actual one for the soil samples, as it has been shown to increase with the height of the core (Klute, 1986). Longer time to carry out the experiment is another disadvantage of the method.

Field methods for soil water retention determination

Reliable water content-matric potential relationship is fundamental to the characterization of available water capacity, water retention and flow of water in the soil. Evaluation of the water content-matric potential relationship $\theta(\psi)$ in the field requires considerable time and effort as well as much equipment (Luxmore and Bruce, 1986). According to Luxomore and Bruce (1986) two common field methods are in use for water retention. These are the methods used for 0-50 kPa pressure range and the evapotranspiration range of potentials. Variability in field situation, incomplete wetting of field soil volumes because of air-entrapment or macropores flow, and our inability to describe the situation with the existing field measurement technique are the main setbacks of these methods.

2.2.2 Direct determination of soil hydraulic conductivity

Laboratory methods for determination of soil hydraulic conductivity

Existing techniques for obtaining soil hydraulic conductivity are numerous, and each can be characterized by its assumptions and level of complexity (Marion *et al.*, 1994). In the literature many measurement techniques have been proposed for hydraulic conductivity determination. Distinction is mostly made between measurements of the saturated hydraulic conductivity (K_s) and the unsaturated (K) one; saturated hydraulic conductivity being much easier to measure (Klute and Dirksen, 1986). In the laboratory the K_s is determined by a constant or falling head method (Klute and Dirksen, 1986). Measurement of the hydraulic conductivity of saturated soil in the laboratory is based on the direct application of the Darcy equation to a saturated soil column of uniform cross-sectional area. A hydraulic head difference is imposed on the soil column, and the resulting flux of water is measured. The conductivity is given by:

$$K_s = \frac{VL}{\left[At\left(H_2 - H_1\right)\right]} \tag{1}$$

Where V is the volume of water that flows through the sample of cross-sectional area A in time t; (H_2-H_1) is hydraulic head difference imposed across the sample of length L (Klute and Dirksen, 1986). Other laboratory methods for saturated soil hydraulic conductivity determination include the steady state flux control method, instantaneous profile method, inflow-outflow through a high-resistance porous plate (Klute and Dirksen, 1986) and the method of Bouma *et al.* (1983).

Determination of hydraulic conductivity in unsaturated soil is based on the application of Darcy's equation and by assuming that the hydraulic conductivity is a function of the degree of saturation of the medium (Klute and Dirksen, 1986). The measurement of unsaturated hydraulic conductivity at a given water content, K(θ), or matric potential, K(h), is classified into steady state and non steady state or transient flow methods (Vereecken, 1988). In the steady state methods the volumetric flux and the hydraulic gradient are measured in a system of time non-variant flow, while in the non steady state method the system is time-variant. According to Vereecken (1988) well known steady state methods are the methods of Moore (1939), the infiltration method of Youngs (1968), infiltration through any impeding layer (Hillel and Gardner, 1970) and the crust method of Bouma *et al.* (1983). Methods belonging to non steady state among others are the outflow method of Gardner (1956), the Boltzman transformation methods (e.g. horizontal infiltration) (Klute, 1986) and the instantaneous profile method (Watson, 1966)).

2.2.3 Field methods for determination of soil hydraulic conductivity

Several methods have been developed for determining the saturated hydraulic conductivity in the field. They include methods applied to areas with shallow water tables as well as those with deep water tables (Amoozegar and Warrick, 1986). In the field the auger hole or inverse auger hole and infiltrometer test (disc permeameter or tension infiltrometers and double ring) are commonly used to give estimates of saturated hydraulic conductivity of soils.

Auger-hole method for field determination of saturated soil hydraulic conductivity

The auger-hole method is the field procedure most commonly used for *in situ* determination of saturated hydraulic conductivity (K_s) of soils. This method has many possible variations (Amoozegar and Warrick, 1986). In its simplest form, it consists of the preparation of a cavity partially penetrating the aquifer, with minimal disturbance of the soil. After preparation of the cavity, the water in the hole is allowed to equilibrate with the groundwater, that is, the level in the hole becomes coincident with the water table level. The actual test starts by removing the entire amount of water from the hole and by measuring the rate of the rise of the water level within the cavity. Measuring rate of rise is stopped before the hole becomes half full. Several measurements of rise are taken after removing water from hole. Because of the three-dimensional aspect of the flow pattern of the water near the cavity, there is no simple equation for accurately determining the conductivity. Numerous available semi-empirical expressions, however, can be used for approximating the saturated hydraulic conductivity for different soil configurations. These expressions are functions of the geometrical dimensions of the auger hole, aquifer and the measured rate at which the water level in the hole changes with time (Amoozegar and Warrick, 1986). The auger-hole method is applicable to an unconfined aquifer with homogeneous soil properties and a shallow water table. This method provides an estimate of the average horizontal component of the saturated hydraulic conductivity of the soil within the aquifer. Enhanced variations of the method have been developed to account for layered soils and for the determination of either horizontal or vertical components of saturated hydraulic conductivity. Results obtained by the auger-hole method are not reliable for cases in which (1) the water table is above the soil surface, (2) artesian conditions exist, (3) the soil structure is extensively layered, and (4) highly permeable small strata occur.

Piezometer method for field determination of saturated soil hydraulic conductivity

The piezometer method, like the auger-hole method, is applicable for determining saturated hydraulic conductivity of soils in an unconfined aquifer with a shallow water table. Unlike the auger-hole method, however, the piezometer method is appropriately designed for applications in layered soil aquifers and for determining either horizontal or vertical components of the saturated hydraulic conductivity. This method consists of installing a piezometer tube or pipe into an auger hole drilled through the subsurface system without disturbing the soil. The piezometer tube should be long enough to partially penetrate the unconfined aquifer. The walls of the piezometer tube are totally closed except at its lower extremity, where the tube is screened open to form a cylindrical cavity of radius r and height hc within the aquifer. The water in the piezometer tube is first removed to clean the system and is then allowed to equilibrate with the groundwater level. Similar to the auger-hole method, the piezometer method is conducted by removing the water from the pipe and then measuring the rate of the rise of the water within the pipe. The saturated hydraulic conductivity is then evaluated as a function of the geometrical dimension of the cavity in the piezometer tube, the dimensions of the aquifer, and the measured rate of rise of the water table in the tube. The value for the conductivity is calculated with the help of a nomograph and tables (Amoozegar and Warrick, 1986).

Depending on the relative height (hc) of the cavity as compared with its radius (r), the piezometer method can be used to determine the horizontal or vertical component of the saturated hydraulic conductivity. Thus, if hc is large compared to r, the results obtained reflect the horizontal component of K_s. Otherwise, if hc is small compared to r, then the vertical component of K_s is estimated. The piezometer method is especially suitable for determining the conductivity of individual layers in stratified subsurface systems (Amoozegar and Warrick 1986).

Tension infiltrometer (Disc permeameter) for field determination of K_s

The tension infiltrometer has become a popular instrument for field determination of soil hydraulic properties such as hydraulic conductivity of saturated soil (Reynolds and Elrick, 1991; Wang *et al.*, 1998). The disc permeameter allows the determination of hydraulic conductivity over a range of negative potentials. Water is supplied to the soil through a porous membrane from a water tower. The required potential of this water is set by adjusting the height of water in a second smaller bubble tower. Such things as soil hydraulic conductivity, soil diffusivity, macroscopic capillary length and representative pore size can be measured (White, 1992).

The advantages of using a disc permeameter are that it is very easy to set up, operate and transport. Obtaining data from these permeameters is a lot easier than the double ring infiltrometer, although it is a lot more complicated to analyse due to the flow being in three dimensions, unless set so that the flow is in one dimension. When analysing these data absorption and capillary forces, which act in all directions, and the geometry of the water source have to be considered (White, 1992). A good intimate contact between the disc and the soil surface also needs to be established. This is often achieved by using a contact material such as fine sand. A drawback of using such a material is that it will interfere with the measurements especially in the early stages of infiltration giving inaccurate sorptivity values (White, 1992). Other limitations are such as time to reach the steady state condition is much higher than the expected time in some soils and in freshly tilled soils, sometimes contact material properties dominate at early stages.

Double ring infiltrometer for determination of saturated soil hydraulic conductivity

The double ring infiltrometer can be used to measure saturated hydraulic conductivity of the soil, and consists of an inner and outer ring inserted into the ground. Both the inner and the outer rings are supplied with a constant head of water. Hydraulic conductivity can be estimated from the constant final steady state infiltration rate in the inner ring (White, 1992) or by multiplying the final steady state infiltration rate with a constant such as that of the method of Young (1968). Having the two rings eliminates the problem of overestimating the hydraulic conductivity in the field due to three-dimensional flow. The outer ring supplies water, which contributes to lateral flow so that the inner ring is contributing to the downward flow.

Some drawbacks of the double ring are that it is very time consuming. The practicality of the instrument is reduced by the fact that the rings are extremely heavy to move. It also requires a flat undisturbed surface, which sometimes is not available and considerable amounts of water. True estimates of K_s can be obtained by the instrument because it operates without any imposed restrictions. Other standard methods for measuring field-saturated K_s include (1) the shallow-well pump-in or dry auger-hole, (2) the double-tube, and (3) the constant-head test in a single drill hole. Further detailed discussion on these standard methods can also be found in Amoozegar and Warrick (1986). The results of these *in situ* measurements of K_s are commonly called the field-saturated hydraulic conductivity.

Applications of soil water flow theory to many practical problems require estimates or measurements of hydraulic conductivity for unsaturated soil over the water content range of interest (Green *et al.*, 1986). Several methods exist for measuring unsaturated hydraulic conductivity; the commonest one being the unsteady drainage flux method (often called the instantaneous profile method) (Green *et al.*, 1986). Other methods according to Green *et al.* (1986) are simplified unsteady drainage flux method, crust-imposed steady flux method and sprinkler-imposed steady flux method.

2.3 Selected Methods for Soil Hydraulic Properties Measurement

2.3.1 Soil moisture retention

Direct laboratory method for soil water retention characteristics will be used in this study. Although field methods are considered as standard against laboratory methods, they are selected for use in this study because:

1. Materials and time do not guarantee use of field methods such as field tentiometers due to the nature of the study which requires soil profiles to be opened on different sites of the study area and where other measurements including the soil hydraulic properties will be done;
2. Equipment to carry out the measurement (suction cell and pressure plate for low and high suction moisture retention) are available;
3. The results expected from the method are considered to be satisfactory for intended purpose, which is estimation of soil moisture retention estimation from soil physical properties.

2.3.2 Soil hydraulic conductivity

Disc and Double ring infiltrometer field methods for soil hydraulic conductivity are selected for use in this study because of the following reasons (Natai, 1997):

1. The weight of the Disc infiltrometer is very low (approx. 1.4 kg) and, therefore, easier to carry;
2. The Disc infiltrometer is accurate and precise for the application at selected tensions;
3. Easy filling of reservoir, low water requirements (1.5 litres), and minimal disturbance of the soil surface;

4. Although the practicality of the Double ring infiltrometer is reduced due to the fact that the rings are heavy to move, steady state infiltration rates obtained using the method are regarded as a true estimate of K_s of a particular soil because its operation is under zero or positive pressure (atmospheric pressure).

2.4 Estimation Methods for Soil Hydraulic Properties

Pedotransfer functions (PTFs) are often used to estimate soil hydraulic properties when direct measurements are too expensive or cumbersome (Schaap and Leij, 1998). Pedotransfer functions can be used to relate basic soil properties such as texture, bulk density and organic matter content (among others) to soil water retention characteristics (WRC) and soil saturated or unsaturated hydraulic conductivity. It is necessary and useful to develop simplified empirical models to estimate the soil water retention and saturated hydraulic conductivity from easily measurable physical properties (Jabro, 1992). Numerous attempts have been made to predict soil hydraulic properties from soil characteristics such as particle size distribution, bulk density, effective porosity and organic carbon content using PTFs (Gupta and Larson, 1979; Arya and Paris, 1981; Rawls *et al.*, 1982; Haverkamp and Parlange, 1986; Vereecken *et al.*, 1989; Van den Berg *et al.*, 1997; Tomasella and Hodnett 1998; Tomasella *et al.*, 2000).

2.4.1 PTFs for estimating soil WRC

There are basically three methods for estimating soil water retention. These are point regression method, physical model method and functional parameter regression method (Tietje and Tapkenhrich, 1993; Gowing and Young, 1996; Tomasella *et al.*, 2000).

Point regression method

The Point regression method attempt to predict water content at certain discrete matric potentials mainly by means of regression analysis from available soil physical properties. Work in this field among others includes that by Gupta and Larson (1979) Rawls *et al.* (1982, 1983), Saxton *et al.* (1986), Van den Berg *et al.* (1997) and Tomasell and Hodnett (1998).

Gupta and Larson (1979) used multiple linear regression (Eq. 2) to predict the soil water content (θ_p, m^3m^{-3}) at given potentials.

$$\theta_p = a(\%\ sand) + b(\%\ silt) + c(\%\ clay) + d(\%\ organic\ matter) \\ + e(bulk\ density, g/cm^3) \qquad (2)$$

Where *a*, *b*, *c*, *d* and *e* are regression coefficients. Intermediate values of moisture content and matric potential could be linearly interpolated between the calculated points. Use of these equations outside the laboratory is very questionable especially for values in the wet range of the soil moisture retention (Vereecken, 1988). Further more, the derived equations contain one variable (% sand) which is a linear combination of the two other textural variables, and thus containing no new information. Perfect linear combinations can also have a deleterious effect on the variances of the regression coefficients (Vereecken, 1988).

Rawls *et al.* (1982) presented three different models for predicting soil water content at each selected matric potential using soil texture (percent sand, silt and clay), bulk density, and organic matter content. In addition to texture, water contents at field capacity and or permanent wilting point are included in some of these models. The coefficients of the linear multiple regression equations at the selected matric potentials among those developed by Rawls *et al.* (1982) are given in Table 2.1 below.

Table 2.1. Coefficients of linear regression equations for prediction of soil water contents at specific matric potentials

Matric potential (kPa)	Mo del no	Intercept	Sand (%)	Silt (%)	Clay (%)	OM (%)	BD (g/cm^3)	FC (m^3/ m^3)	PWP (m^3/ m^3)	r
-10	1	0.4118	-0.003		0.0023	0.0317				0.81
	2	0.4103	-0.0031			0.0260			0.41	0.81
	3	0.0619	0.002			0.0067		1.34	-0.51	0.95
-33	1	0.2576	0.002		0.0036	0.0299				0.87
	2	0.2391	-0.0019			0.021			0.72	0.92
-60	1	0.2065	-0.0016		0.004	0.0275				0.87
	2	0.1814	-0.0015			0.0178				0.94
	3	0.0136					-0.0091	0.66	0.80	0.99
-100	1	0.0349		0.0014	0.0055	0.0251				0.87
	2	0.01417	-0.0012			0.0151			0.85	0.96
	3	-0.0034				0.0022		0.52	0.54	0.99
-1500	1	0.026			0.05	0.0158				0.80

e.g. θ_{10kPa} (Model one) = 0.4118-0.0030(% sand)+0.0023(% clay)+0.0317(% OM) (r =0.81) Source: **Rawls *et al.* (1982)**

Where OM is the organic matter, BD is the bulk density, FC is the field capacity, PWP is the permanent wilting point and r is the correlation coefficient. Rawls *et al.* (1983) presented a set of regression equations for soil WRC based on percent sand, clay, OM, and BD. The coefficients of these equations are as shown in Table 2.2.

Table 2.2. Coefficients for linear regression equations of prediction of volumetric soil water contents at specific matric potentials

		Coefficient for independent variables				r^2
Matric potential (kPa)	Intercept	Sand %	Clay %	OC %	BD (g/cm^3)	
-33	0.3486	-0.0018	0.0039	0.0228	-0.0738	0.88
-60	0.2819	-0.0014	0.0042	0.0216	-0.0612	0.88
-100	0.2352	-0.0012	0.0043	0.0202	-0.0517	0.87
-1500	0.0854	-0.0004	0.0044	0.0122	-0.0182	0.81

eg.θ at –33kPa =0.3486-0.0018(% sand)+0.0039(% clay)+0.228(% OM)-0.0738BD (r^2=0.88)
Source: Rawls *et al.* (1983)

For all matric potentials except –1500 kPa, calculated water contents were appreciably larger than the measured values (mean error) ranging from 0.104 to 0.0073 m^3/m^3 decreasing with the decrease in potential from –10 to –1500kPa. Models 2 (Rawls *et al.*, 1982) for selected matric potentials were not much better in overall performance than models 1. Incorporating water contents at –33 and –1500 kPa potentials in model 3 as independent variables, at respective matric potentials significantly improved the calculated results (Ahuja *et al.*, 1985). Tomasella and Hodnett (1998) found that the equations of Rawls *et al.* (1982, 1983) for example overestimate water contents when applied to tropical soils of the Brazilian Amazonia. Thus the usability of these equations in the study area is not guaranteed.

Saxton *et al.* (1986) used equations developed by Rawls *et al.* (1982) for matric potentials greater than 10 kPa to estimate moisture content at given matric potential. Values for textures with > 60 % clay content, < 5 % sand and < 5 % clay were omitted from the regression equations because they exceeded the range of all but a few of the original data used in statistical analysis by Rawls *et al.* (1982). The percentage of sand and clay were correlated with the parameters A and B given in equation (3) below. The regression equations for the parameters A and B are as given by equations (4) and (5).

$$\psi = A\theta^{B} \tag{3}$$

Where ψ (kPa) is soil matric potential and θ (cm^3cm^{-3}) is soil water content.

$$A = \exp[-4.396-0.0715\,(\%\,clay)-4.88\times10^{-4}\,(\%\,sand)^2$$
$$-4.285\times10^{-5}\,(\%\,sand)^2(\%\,clay)]\times100 \tag{4}$$

$$B = -3.14-0.00222(\%\,clay)^2-3.484\times10^{-5}(\%\,sand)^2(\%\,clay) \tag{5}$$

At given matric potential, the moisture retention could easily be determined using equation (3) after estimating parameters A and B from percentage clay and sand.

The developed PTFs were tested over the range of applicability to determine areas of unreasonable result. At low and high clay contents, the estimates of soil water content exceeded the saturation water content (Saxton *et al.*, 1986), which in reality is not possible.

Van den Berg *et al.* (1997) used multiple linear regression equations to correlate water retention to soil properties such as soil texture, bulk density and specific surface area (SS) at matric suctions of 10 kPa, 1500 kPa and AWC (difference between 10 and 1500 kPa in his study). The soil textural fractions used were sand

(0.05-2 mm), silt (2-50 µm) and clay (< 2 µm). Clay content accounted for the largest variation in moisture content retained at 10 kPa, which increased with the addition of silt and OC contents. Specific surface area explained the same amount of variation as clay content. The regression equations with the highest r^2 at each matric suction used are as shown in Table 2.3 below.

Table 2.3. Regression equations for moisture retention as a function of measured soil properties at matric potentials of 10 and 1500 kPa and AWC

Dependent variable	Regression equation	r^2	Residual variance
θ_{10kPa}	12.19+0.212Clay+0.208Silt+0.107SS	0.87	13.1
$\theta_{1500kPa}$	$0.344Clay_{vol}+0.104Silt_{vol}$	0.83	10.3
$\theta_{10kPa-1500kPa}$	24.85-0.114Clay+0.090SS-10.53BD	0.48	10.9

θ= volumetric water content in %; clay, silt, and sand are in % mass fractions; $Clay_{vol}$ and $Silt_{vol}$ are in % of mass volume of soil; BD (g/cm^3); and SS (m^{2}g^{-1})

Source: Van den berg *et al.* (1997)

The accuracy of the developed PTFs were acceptable. However, soils analysed in this study were all well drained, strongly weathered, had relatively low OC contents, and the ranges of applicability of these PTFs was not clearly specified for low activity clays (LAC). Therefore, the PTFs could not be directly used in the current study area. The results obtained from limited sets of data used in the study do not allow extrapolation to soils else where in the world, but do warrant further work (Van den Berg *et al.*, 1997).

Tomasella and Hodnett (1998) developed multiple linear regression equations of the form shown in Eq. 6 to estimate water contents from soil texture (% sand, silt and clay) for matric potentials ranging from –1 to –1500 kPa. Table 2.4 shows the coefficients of the developed regression equations.

$$\theta(\psi_i) = a_i OC + b_i Si + c_i Cl \qquad (6)$$

Where $\theta(\psi)$ is the soil water content at given matric potential, OC is organic carbon (%), Si is silt (%), Cl is clay (%) and a, b, are constants.

Table 2.4. Coefficients of multiple linear regressions for the prediction of volumetric water content (% cm^{3}cm^{-3}) as a function of texture for selected matric potentials (values in parentheses indicate the standard error)

Eq. No. l	Matric potential, kPa	Intercept	Silt %	Clay %	No. of data points	r
1	-1	23.839	0.530 (0.018)	0.225 (0.019)	196	0.902
2	-3	18.495	0.552 (0.017)	0.262 (0.017)	196	0.920
3	-6	12.333	0.576 (0.017)	0.300 (0.018)	196	0.922
4	-10	9.806	0.543 (0.016)	0.321(0.015)	234	0.918
5	-33	4.046	0.426 (0.015)	0.404 (0.012)	416	0.882
6	-100	3.198	0.369 (0.015)	0.351(0.015)	196	0.897
7	-500	1.567	0.258 (0.016)	0.361(0.016)	196	0.859
8	-1500	0.910	0.150 (0.013)	0.396 (0.010)	416	0.889

eg. at –1 kPa, the regression equation is $\theta(1\text{ kPa}) = 23.839+0.530(\%\text{ silt})+0.255\ (\%\text{ clay})$, (r =0.902). **Source: Tomasella and Hodnett (1998)**

Since Equation 6 is linear, the inclusion of percentage of sand, which is a linear combination of the percentage of silt and clay, could not provide additional information. There were high correlation coefficients for the developed regression equations. The agreement between measured and estimated water contents was remarkable despite the wide range of soils used in the regression (Tomasella and

Hodnet, 1998). The equations may be applicable in the proposed study area because the textural fraction from the study falls within the ranges of applicability of these equations.

Relatively simple regression techniques can be used to build a mathematical model between data points of the hydraulic characteristics and soil properties for point regression methods making a straight forward estimation of soil water retention (Vereecken, 1988). Some of the problems associated with the methods under this group include the discrete nature of the water content against matric potential points generated, requiring interpolation and even extrapolation for tension/water contents not estimated if moisture retention curve is desired (Gowing and Young, 1996).

Physical model method

Physical model method calculates soil moisture retention and matric potential from a three-stage process, which first calculates the pore size-distribution from the particle size distribution. The water content is then predicted from the pore-size distribution according to conservation of mass and finally the matric potential is predicted from the water content according to the equation of capillarity (Arya and Paris, 1981, Vereecken, 1988, Tietje and Tapkenhinrichs, 1993). Models under this group include those developed by Arya and Paris (1981), Harverkamp and Parlange, (1986) and Tyler and Wheatcraft (1989).

The physical model methods can be adopted in any situation provided calibration is done to suit the particular soil condition. Most soil hydrological databases contain less than seven fractions, which are considered sufficient. However, particle size distribution should be as detailed as possible. This is one of the biggest limitations for the use of this type of models. The use of only three fractions (clay, silt and sand) reduces the performance considerably because the method estimates one point on the retention function from each fraction (Tietje and Hennings, 1993). Serious deviations can also be obtained between measured and estimated water contents at respective matric potentials for surface soil materials with aggregation, cracking and for swelling and shrinking soils (Vereecken, 1988).

Functional parameter regression method

For the parameter regression method, a certain closed form function is assumed for the relation between ψ (matric potential) and θ (moisture content). These closed form functions are such as the Brooks and Corey (1964) and van Genuchten (1980) equations for soil water retention characteristics. Methods under parameter regression among others include Cosby *et al.* (1984), Rawls and Brankensiek (1989), Vereecken *et al.* (1989), Van den Berg *et al.* (1997), Tomasella and Hodnett (1998), and Tomasella *et al.* (2000).

Parameter regression models offer a lot of possibilities such as the generation of a large measurement range for hydraulic properties from only few measurements of soil hydraulic/physical properties. Appropriate choice of a model for the soil moisture retention characteristics could for instance result in closed form equations for the different hydraulic conductivity models (Vereecken, 1988). Also the use of non-linear multiple regressions lead to general applicability to almost all soils

(Vereecken, 1988). This is an important aspect for PTFs used for hydrological modeling purposes. The setbacks for these type of models is that a need exists to find an appropriate model for predicting the hydraulic characteristics especially when large data sets and different competitive models with varying degree of complexity are involved. Improperly selected models may lead to inaccurate estimations of soil hydraulic properties. Parameter regression models are known to be nonlinear and needing nonlinear parameter estimation techniques. These techniques are often difficult to handle and the resulting estimates are not always accurate (Vereecken, 1988).

Tietje and Tapkenhinrichs (1993) compared measured soil water retention characteristics with those estimated by the three types of PTFs using 1079 German soils covering the majority of possible soil textures. The tested PTFs among others were the Gupta and Larson (1979) for point regression methods; Arya and Paris (1981) under physical model approach and Vereecken *et al.* (1989) for the parameter regression methods. Water contents were either slightly or highly over estimated at some matric potentials by the method of Gupta and Larson (1979). High soil organic carbon (> 10 %) led to underestimation of soil water retention by the Arya and Paris (1981) model. Though there were high deviations for soils with low bulk densities, the model of Vereecken *et al.* (1989) produced the lowest mean differences between measured and estimated soil moisture retention (Tietje and Tapkenhinrichs, 1993). These PTFs when used on tropical soils have been shown to give unreliable results even when the soils are within their range of validity. In most of these PTFs water contents are either strongly over-or under-estimated, showing the limitations of these regression functions for estimating the water retention characteristics of tropical soils in which the pedogenic and biological processes are different.

Pedotransfer functions of Tomasella and Hodnett (1998) and Tomasella *et al.* (2000) are among the few PTFs, which have been shown to give reliable WRC predictions for tropical soils. In the current work PTFs of Tomasella and Hodnett (1998) will be evaluated using soil properties data from the study area at pre-determined matric potentials.

The reasons for selecting these PTFs for evaluation are that the functions were developed and tested using tropical soils having more-or-less similar properties to the study area. Textural fraction from previous studies (Kaaya, 1989 and Gowing and Young, 1996) in the study area were found to be within the ranges used in testing the PTFs. The mean values of the textural fraction used in validation of the PTFs were 41% (5.7-81.6%) for sand, 16.5% (3.5-43.9%) for silt and 42.5% (11.6-77.4%) for clay (Tomasella and Hodnett, 1998). The methods used in developing the functions were simple and the correlation coefficients were very high for the developed PTFs indicating good agreement between measurements and estimations. The equations derived were exclusively for tropical soils and comparison between measured and estimated values of water contents showed significant correlation (Tomasella and Hodnett, 1998).

2.4.2 PTFs for estimating soil hydraulic conductivity

Three estimation methods for soil hydraulic conductivity (SHC) from physical soil properties can be recognized. The first method estimates SHC by regression from input variables such as soil texture, organic matter content and bulk density using regression equations (Tietje and Hennings, 1996, Gowing and Young, 1996). This type includes methods developed by Ahuja *et al.* (1984), Cosby *et al.* (1984), Brakensiek *et al.* (1984), Saxton *et al.* (1986), Vereecken *et al.* (1990) and Jabro (1992). The second group determines the SHC from the physical empirical relationship between particle size distribution and conductivity. Methods under this category include Bloemen (1980), Campbell and Campbell (1982) and Campbell (1985) among others (Tietje and Hennings, 1996). The third group uses the functional parameter regression method in theoretically developed models such as the Mualem (1976) and Gardner (1958) for soil hydraulic conductivity (Gowing and Young, 1996).

Campbell and Campbell (1982) correlated conductivity values from Bloemen (1980) with silt plus clay content of the soil to obtain the following equation:

$$K_s = 70.59 exp[-4.26(m_s+m_c)] \qquad (7)$$

Where K_s is the saturated hydraulic conductivity in cm/h and m_s and m_c are silt and clay mass fractions in percent. The equation has generally correct response to texture but has a great sensitivity to silt fraction (Campbell, 1985). Campbell (1985) suggested that an equation, which weighs clay more heavily than silt, would give better results. He developed the following equation for estimating K_s:

$$K_s = C\,exp(-6.9m_c - 3.7m_s) \qquad (8)$$

Where C is a constant. Best fit of the soil data from several sources appears to occur when C=141.176 cm/h (Campbell 1985). Calculated values of K_s from Equations (7) and (8) were generally in good agreement with values calculated by other methods such as the Israelsen and Hansen (Campbell, 1985). Campbell (1985) suggested the following equation, which includes bulk density:

$$K_s = 339(1.3/b_d)^{1.3b} exp\,(-6.9c - 3.7u)\ (cm/d) \qquad (9)$$

Where $b = GMPS^{-0.5} + 0.2.GSD$, GMPS = geometric mean particle size (mm), GSD = geometric standard deviation, b_d = bulk density, (gcm^{-3}), u = silt content (%), c= clay content (%). The approach in developing the equation was based on the assumption that the particle size distribution is approximately log-normally distributed and can be represented by GMPS and GSD.

Equations 8 and 9 cannot be used to correctly predict the saturated hydraulic conductivity of a soil which contains large interconnected cracks, worm holes or root channels because they have large hydraulic radii, which conduct water much faster than uniform soils (Campbell, 1985). Equation 9 becomes more and more inaccurate for soils with bulk density below 1 g/cm^3, which cannot be compensated by neglecting the bulk density effect (Tietje and Hennings, 1996). The accuracy and the range of applicability of these equations are not specified and therefore the usability of the equations on different soils is questionable unless they are calibrated for the particular soil.

Ahuja *et al.* (1984) proposed a generalized Kozeny-Carman equation relating the K_s to effective porosity (ϕ_e) (total porosity minus water content at –33 kPa matric potential) in the following form:

$$K_s = C\phi^m_e \tag{10}$$

Where C and m are empirically derived constants. Several authors have found C to vary between 440 and 34,000 and m to vary between 1.59 and 3.98. Both constants vary with soil type making the equation universally unusable (Rawls *et al.*, 1998). Also the interrelation between C and m makes it difficult to distinguish the soil effect on the constants.

Saxton *et al.* (1986) developed an equation for K_s estimation from multiple non-linear regression techniques using percent sand, clay and moisture content as the independent variables to develop the following equation:

$$K_s=24\ exp[12.012-0.0755(\%\ sand)+[-3.895+0.03671\ (\%\ sand)-0.1103\ (\%\ clay)+8.7546\ x10^{-4}\ (\%\ clay)^2](1/\theta_s)]\ (r^2=0.95) \tag{11}$$

Where $\theta_s = 0.332-0.0007251(\%\ \text{sand}) + 0.1276\ \log_{10}(\%\ \text{clay})$. The correlation coefficient for the developed equation was very high and it gave quite reasonable values over the same textural ranges used in model development (Saxton *et al.*, 1986). For extreme conditions of near saturation or very dry and very high clay contents, the calculated values did not match desirably reported values (Saxton *et al.*, 1986).

Rawls and Brakensiek (1989) developed regression equations for estimating K_s from texture and bulk density using soils found in the USA. Conductivity at field saturation, wetting front suction and water content at field saturation could be estimated with reasonable degree of accuracy for soils with sand content of between 5% and 70% and clay content of between 5% and 60% (Young and Gowing 1996). Among the PTFs developed by Rawls and Brakensiek (1989) is the following:

$$K_s = exp\,((19.52348\phi)\text{- }8.96847\text{-}(0.028212\,(cl))+(0.0018107(Sa)^2 - (0.0094125\,(Cl)^2)\text{- }(8.395215\phi^2\,)$$
$$+\,(0.077718\,(Sa)\,\phi)\text{- }(0.00298(Sa)^2\,\phi^2)\text{-}(0.019492\,(Cl)^2\phi^2)\,\div$$
$$(0.0000173(Sa)^2(Cl))+(0.02733(Cl)^2\phi)+(0.001434(Sa^2)\,\phi)\text{-}(3.3\text{x}10^{-6}(Cl)^2(Sa))) \qquad (12)$$

Where Cl = % clay content, Sa = % sand content, ϕ = % total porosity (cm^3cm^{-3}). Salim (1999) used equation (12) to estimate K_s for soils found in some parts of SUA farm. The values for K_s varied from $6\text{x}10^{-4}$ to 1.0954 cm/h. Values of K_s were found to decrease with increase in clay content. However, no comparative measurements were provided and therefore the accuracy in estimation was not specified. Also the equation is complex hence posing difficulties in applicability.

Vereecken *et al.* (1990) developed the following regression equation for estimating K_s:

$$K_s = exp[20.62\text{-}0.96ln(c) - 0.66ln\,(s) - ln\,(m)\text{-}8.43b_d]cm/d \qquad (13)$$

Where s = sand content (%) (50-200 μm), c = clay content (%) (< 2μm), m = organic matter (%) and b_d = bulk density (g/cm^3). The K_s used in developing the regression equation were measured with the crust method using larger soil columns (greater than 600cm^3). Estimation using this method led to higher values of K_s especially for clay and silt clay soils than the laboratory measurements (Tietje and Hennings, 1996). This could have been due to the estimation method used within the investigation (Vereecken *et al.*, 1990) which applied larger soil columns for the crust method technique leading to more macropore effects being included when applied to other conductivity data bases obtained by different measurement methods.

Jabro (1992) developed multiple linear regression model for K_s from particle size distribution and bulk density data. The equation has the form:

$$\text{Log}\,(K_s)=9.56-0.81\,log\,(\%silt)-1.09\,log\,(\%clay)-4.64\,(BD) \qquad (14)$$

A stepwise regression selected the best model for prediction of K_s ($r^2=0.68$). Particle size distributions were found to give better results when transformed into logarithmic values. Although there was a high correlation between field measured and predicted SHC values, the data used in the development and testing of the model were from the USA and, therefore, the model cannot be directly applied to a different soil type without validation.

Tietje and Hennings (1996) evaluated some PTFs for estimating K_s using the database of the Lower Saxony Soil Information System in German. The main objective was to quantify the validity of PTFs for estimating K_s against consistent set of measurements. Among the tested PTFs were Cosby *et al.* (1984), Brakensiek *et al.* (1984), Saxton *et al.* (1986), Vereecken *et al.* (1990), Bloemen (1980) and Campbell (1985). Pedotransfer functions of Brakensiek *et al.* (1984), Campbell (1985) and

Bloemen (1980) were found to underestimate K_s while prediction according to Saxton *et al.* (1986), Cosby *et al.* (1984) and Vereecken *et al.* (1990) generally led to higher values than obtained by Laboratory measurements (Tietje and Hennings, 1996). The Campbell (1985) PTFs was observed to underestimate K_s within each texture class. The geometrical standard deviation of the error ratio (GSDER) differed only slightly between most of the PTFs tested, except for Bloemen (1980) which had the largest deviation. The estimations were good for loamy sand; increase in clay content and possible additional effects (e.g. Macropore or shrinking and swelling) deteriorated the prediction (Tietje and Hennings, 1996).

Apart from the general findings, each tested PTF had specific errors in estimating K_s with respect to the textural fractions used. The equations were found to give inaccurate results though the soils used were within the ranges used in developing the equations for some of PTFs. In this work a number of PTFs will be evaluated for K_s estimation using soil physical properties that will be obtained from the study. These PTFs to be evaluated includes methods of Ahuja *et al.* (1984), Campbell (1985), Vereecken *et al.* (1990) and Jabro (1992). The main reason for the selection is that the equations are simple and use variables, which are available in most of the soil survey information. Tietje and Hennings (1996) noted that PTFs only based on grain size distribution and represented by simple regression (e.g. Jabro, 1992) led to similar results than more complex models (e.g. Brakensiek *et al.*, 1989). Also a good coverage for input variables from particle size distribution to porosity is envisaged offering comparisons for K_s obtained from porosity values and particle size distribution.

Saturated hydraulic conductivity of heterogeneous layered soils

Determination of SHC data for PTFs development has been based on small soil core samples (Vereecken *et al.*, 1990, Jabro, 1992, Tietje and Hennings, 1996, Rawls *et al.*, 1998) and, therefore, homogeneous. Values of conductivity measured on small and usually disturbed samples of soil in the laboratory are often poor estimates of conductivity in the field (Yong and Warkentin, 1975; Sankaram, 1980). When a soil layer of different texture and permeability from the surface layer is present in the soil profile, it will affect the K_s as a result of the effect in infiltration rates, regardless of whether it is coarser or finer than the surface layer (Jury *et al.*, 1997). Jury *et al.* (1997) give the following expression for determining the K_s of layered soil referred to as effective saturated hydraulic conductivity (K_{eff}):

$$K_{eff} = \frac{\sum_{j=1}^{N} L_j}{\sum_{j=1}^{N} \left(\frac{L_j}{K_j} \right)} \tag{15}$$

Where N = number of layers, L_j = thickness of layer (cm), K_j = K_s for each layer. The main setback of the proposed method is the necessity of having K_s values for each soil profile layer or horizon.

Hydraulic conductivity can be given for the soil as a whole, for a particular horizon, or for a combination of horizons. The horizon with the lowest value determines the hydraulic conductivity classification for the whole soil. If an appreciable thickness of soil above or below the horizon with the lowest value has significantly higher conductivity, then estimates for both parts are usually given (Soil Survey manual, 1993). Limitation in terms of material and resources does not enable determination of conductivity values for each horizon of soil profiles. The determined K_s values using the Tension and Double ring infiltrometers will be used in the work reported herein as representative K_s values for the entire soil profile for the determined representative soil physical properties (soil texture, BD, and soil porosity) using the procedures explained in the next chapter.

CHAPTER 3

3 MATERIALS AND METHODS

3.1 Location of the Study Site

Sokoine University of Agriculture (SUA) farm is located in Morogoro Municipality, Tanzania, at longitude $37^{0}39'$E and latitude $6^{0}50'$S. It is bordered by the Morogoro Municipality Centre on the east, Uluguru Mountains on the south-east, the Mindu Hills on the west and by Lugala Hills on the north-west (Fig. 1). The total area of the SUA farm is approximately 2300 ha (Mpepo, 1986). The study was conducted on the central part of the farm, which covers approximately 420 ha, and part of the north-west with an area of approximately 2.5 ha (see Fig. 1).

3.2 Climate, Geology and Soils of the Study Area

3.2 1 Climate

The climate at SUA farm is of sub-humid tropical type (Kaaya, 1989). The area has a bimodal rainfall pattern. It has short and lighter rains starting from November and ending in January with the peak in December. These are followed by a short, dry period in mid-January or February. After the dry period the area receives long and heavier rains starting from March and ending in May with a peak in April. The onset and distribution of the rainfall are irregular and unreliable. The study area is normally warm throughout the year with an average temperature of 24^{0}C. The mean minimum and mean maximum temperatures are 18^{0}C and 30^{0}C, respectively (Kapele, 2000).

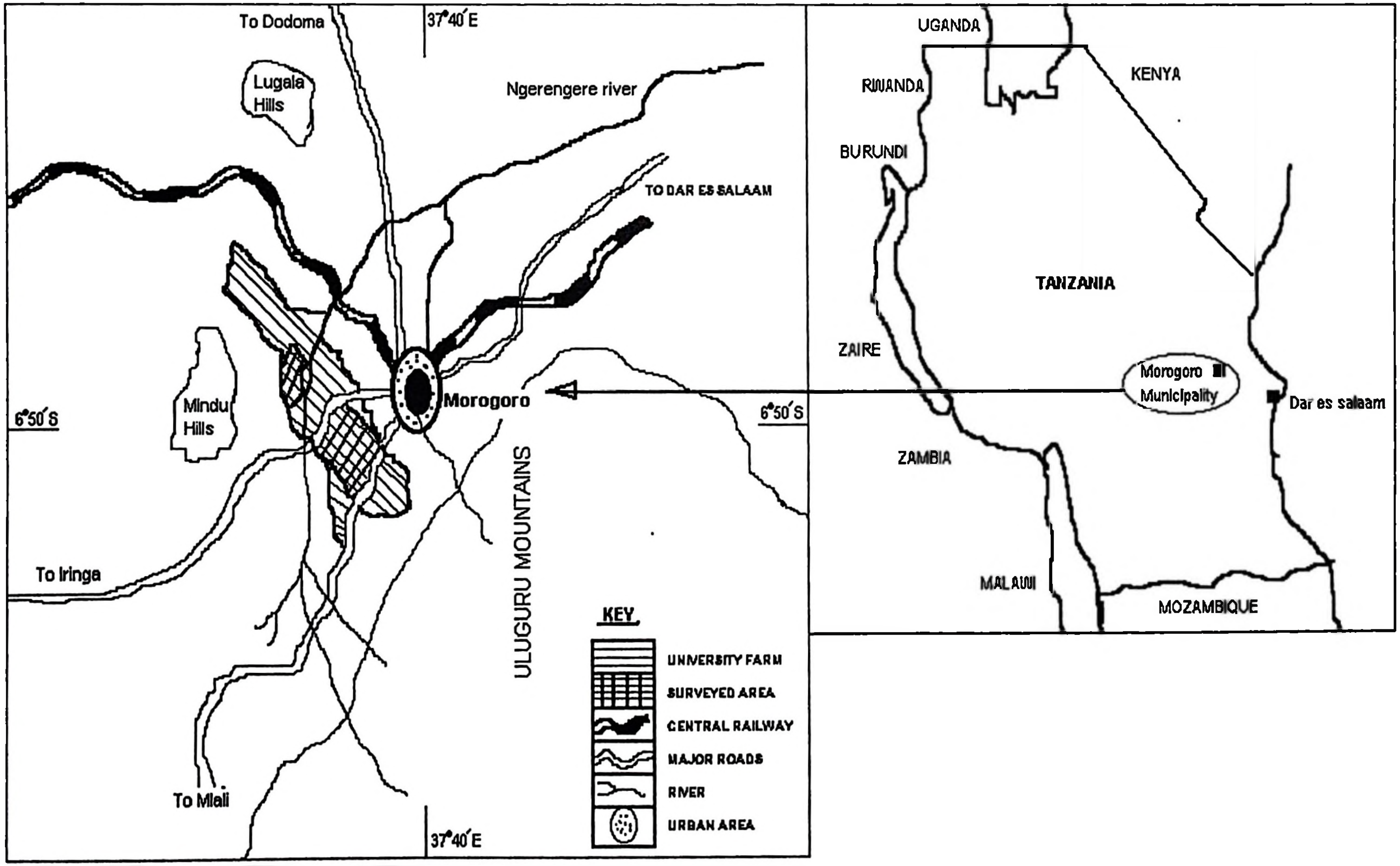

Figure 3 .1. Location of the study area

3.2.2 Geology and soils

The study area consists of soils that are derived from colluvium material from the Uluguru Mountains (Kesseba *et al.*, 1972) and have undergone substantial pedogenesis as expressed by the morphological features (Kaaya, 1989). The geological survey of Morogoro (Sampson *et al.*, 1961) indicates that the study area is covered mostly by red and reddish brown soils. The Uluguru Mountains belong to the Mozambiquan belt. The rocks are metasediments made up of mainly pyroxene granulites containing plagioclase and quartz-rich veins (Kaaya, 1989).

Sokoine University of Agriculture farm has a saucer -like shape (Mpepo, 1986) as it is surrounded by the Uluguru Mountains rising up to a height of over 2,000 metres above sea level (m.a.s.l.), and the Mindu Mountains and Lugala Hills, rising up to heights of 1,200 and 800 m.a.s.l. respectively. The study area generally lies on undulating slopes to almost flat land at an altitude of 480 to 600 m.a.s.l. Soil classification in the study area was done by Mpepo (1986) and Kaaya (1989) using USDA and FAO guidelines. *Nitisols*, *Luvisols* and *Ferralsols* are the main soil types found in the study area.

3.3 Land Use

Cultivation of maize, and research plots under SUA are the main current land use in the study area. Beans and rice are also cultivated in some parts of the farm. Nearly all the natural vegetation in the farm has been disturbed by man through cultivation. The local vegetation is mainly grassland dominated by *Andropogon* spp., *Hyperrhernia* spp. and *Themmeda* spp. (Kaaya, 1989).

3.4 Soil Sampling and Data Collection

Soil map, geological map, topographical map and relevant research reports on the topographic and geological features and soils of the study area were consulted during the preliminary study. Preliminary survey of the study area was done so as to familiarize with the general morphology of the area. Mapping units from the soil survey by Kaaya (1989) on the study area were used for the identification of the locations where field data were to be collected from. At these locations profiles were dug (Fig. 2). At least two locations were identified for each mapping unit. A total of fourteen (14) profiles were studied. Soils were described according to the FAO nomenclature, (FAO 1977, 1990). Soil colour was determined using Munsell Colour Charts (Munsell Colour Company, 1954).

3.4.1 Soil samples for bulk density, moisture content and moisture retention determination

Soil core samplers were used for collection of soil samples for determination of bulk density, moisture content and soil moisture retention. Three undisturbed core soil samples were taken from each horizon of the soil profile (Blake and Hartge, 1986). The following sampling procedure was followed:

1. For each horizon in a soil profile, the soil core was perpendicularly located to the surface of the soil profile;
2. A smooth flat piece of timber was used to press the core from one open end of the core into the soil. Gentle hammering on top of a piece of timber was applied where there was a small resistance in driving the core into the soil due to the soil dryness;

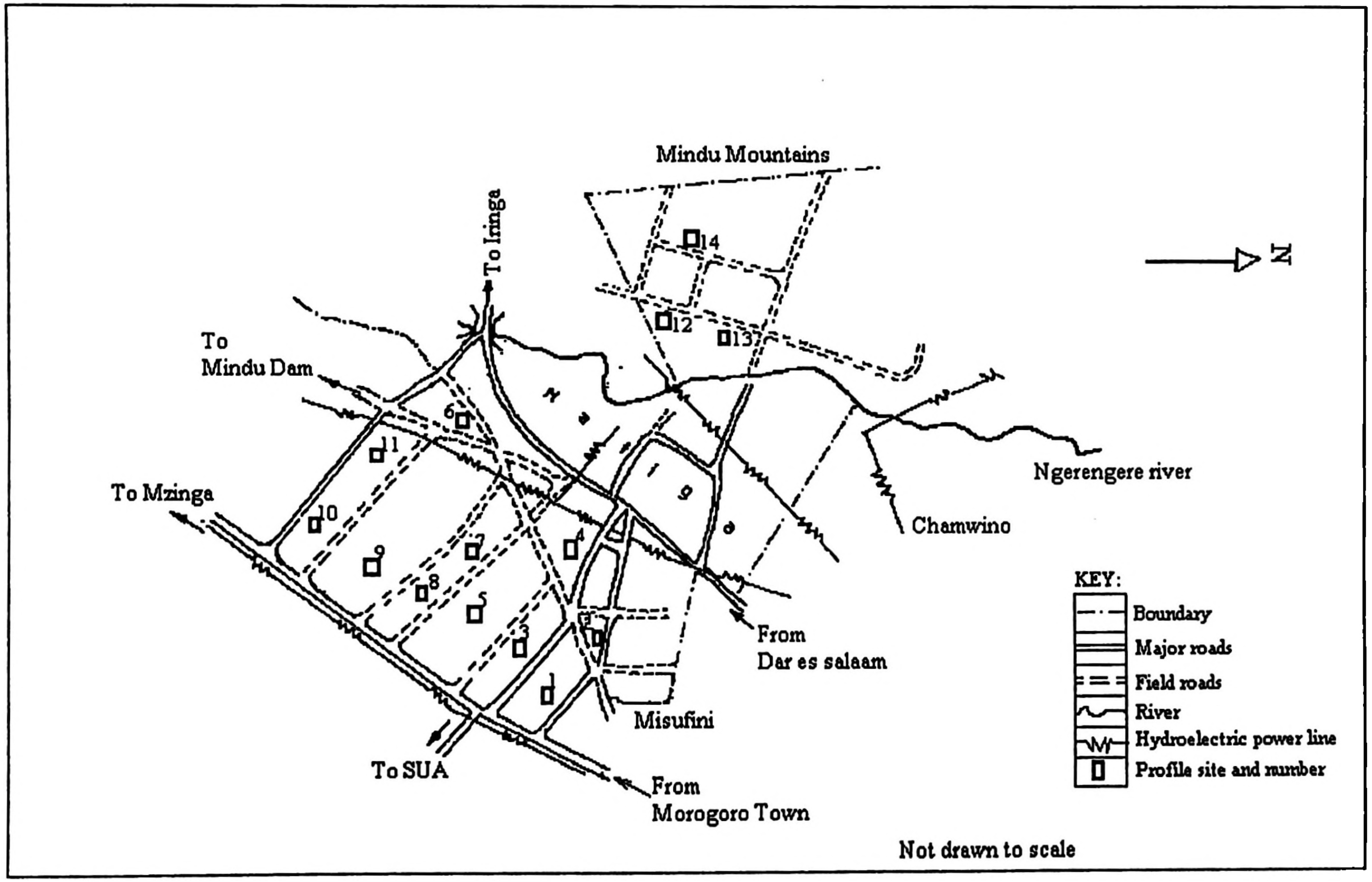

Figure 3.2. Soil profile sites in the study area

3. The core was driven into the soil until at least one centimetre of the soil protruded out of the core;
4. The soil core was carefully removed by excavating the surrounding soil without disturbing soil within the core. This was done so as to as nearly as possible preserve the natural structure and packing of the soil;
5. The soil extending beyond each end of the soil core was trimmed off using a sharp knife;
6. The soil core was immediately covered and packed on the soil core case ready to be taken to the laboratory for analysis.

Similar procedures were followed for all studied soil profiles. During soil sampling care was exercised to avoid compaction of the soils in the cores due to excessive hammering on the core sampler.

3.4.2 Soil samples for texture analysis and organic carbon content determination

A representative bulk soil sample (approximate 1 kg) was collected from each horizon for texture analysis and organic carbon content determination. The samples were put in labelled plastic bags and transported to the laboratory for analysis.

3.5 Data Collection for Soil Hydraulic Conductivity Determination

Data for soil hydraulic conductivity were collected using a Tension infiltrometer (Disc permeameter) and Double ring infiltrometer. The Tension infiltrometer is an instrument that is used in the field to determine soil infiltration rates. The determined infiltration rates (basic or steady state) were then used to calculate the hydraulic conductivity of the soil using procedures outlined in sections 3.7.2 and 3.8.

The tension infiltrometer (Fig. 3) consists of a bubble tower which contains air entry tubes (for tension setting) connected to the bubble tower, the water reservoir in which the water level falls as water flows through the disc with porous membrane and into the soil. The membrane establishes hydraulic continuity with the soil. Infiltration tests were done using the modified tension infiltrometer UNCEL type developed by Environmental Laboratory at the University of NewCastle Upon Tyne UK. The infiltration measurement tests were done at perpendicular distances of three metres from the three end sides of every profile.

3.5.1 Procedure for steady state flow rates determination using the tension infiltrometer

The following procedure was followed in collecting infiltration data from the tension infiltrometer (Bazugba, 2001 and Lwegenzya, 2001):

1. In the field, both the reservoir and bubble tower of the tension infiltrometer (Fig. 3) were filled with water. For the bubble tower, water was added up to the calibrated zero mark. This level served as the zero reference for the tension tubes (air entry tubes). Before connecting the air entry tubes, air inside the tubes was gently blown out. This eliminated the air and water inside the tubes;

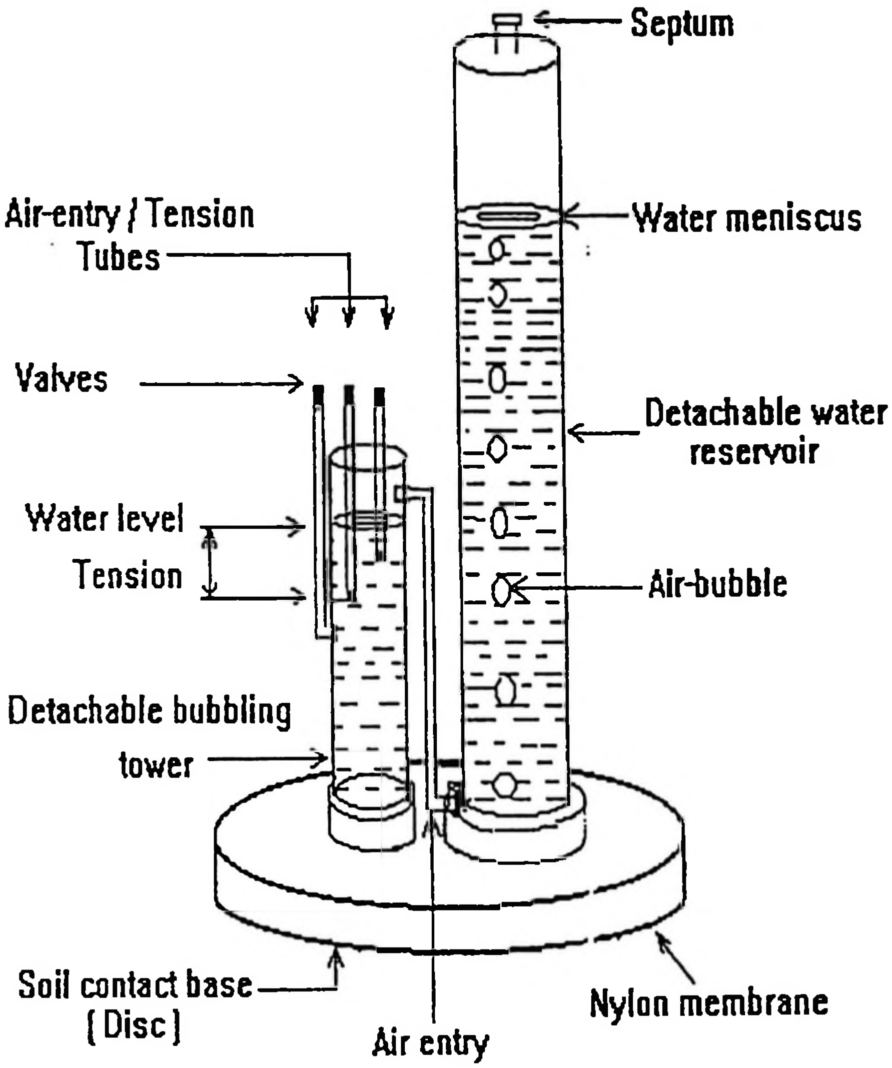

Figure 3.3. Tension infiltrometer (UNCEL type)

2. The soil surface was observed for evidence of cracks, holes, ground level and cleanliness. Where there was tall grass a pair of scissors was used to cut it shot without disturbing the soil surface;
3. The infiltrometer was then carefully placed on top of the smoothed soil surface, covered with a thin piece of cotton cloth (to avoid damage to the membrane). To

make the soil surface level a thin layer of sieved (through a 2 mm sieve) soil materials similar to that where the infiltrometer was set were placed on the ground and leveled using a spirit level before placing the cotton cloth;

4. Before starting measurements the infiltrometer was kept undisturbed for five minutes. This enabled observation of air leakage and equilibration;
5. The valve for the smallest negative pressure (5 cm) was then opened. Shortly after that, air began to bubble through the open-air entry tube in the detachable bublling tower. After observing the first bubble, a stopwatch was started and the time was recorded on a data sheet. The amount of water infiltrating into the soil was recorded against time elapsed by reading on a measuring tape attached to the water reservoir;
6. The steady state flow rate was approximated by observing the change of water level at five minutes time intervals. This observation was repeated until successive changes in water levels were constant for at least three consecutive readings and this took one to one and half hours per tension setting.

After reaching a steady state flow rate, the 7 cm tension valve was opened. The procedure for determining steady state flow with this tension and the procedure for the 10 cm tension was the same as that described for 5 cm tension measurement. Measurement of flow rates with a multiple tension reduces the amount of errors resulting from removing and setting the infiltrometer at each respective tension. The obtained data from the infiltrometer were used for calculating soil saturated hydraulic conductivity (see section 3.7.2).

3.6 Laboratory Analysis of Collected Soil Samples

3.6.1 Determination of soil physical and chemical properties

Soil samples for bulk density were analysed at the SUA Agricultural Engineering and Land Planning laboratory. In the laboratory, core (5 cm) soil samples collected from the field were weighed and the initial weight recorded on a data sheet. The samples were covered with pieces of light and thin cloth towels to hold unstable soil in the cores and then they were placed in a trough. Water was slowly poured (to avoid slaking of soil aggregates) into the trough up to half of the height of the core. The samples were then left to equilibrate (saturate) in standing water for three days. The weight of the samples at saturation was determined. Two weighed saturated samples from each horizon were taken for moisture retention determination. These two samples together with the remaining sample from each horizon were used to determine bulk density after oven drying at 105^0C to constant weight (Blake and Hartge 1986).

Bulk soil samples for texture and organic carbon determinations were air-dried. The samples were ground using a mortar and pestle. The ground samples were taken to the SUA Soil Science laboratory for analysis. Texture was determined by the hydrometer method after dispersing the soil sample with sodium hexametaphosphate (calgon) (Day, 1965). Organic carbon was determined by wet oxidation method of Walkley and Black (Nelson and Sommers, 1996). Soil particle density was assumed to be equal to 2.65 g/cm^3. The value of assumed particle density is usually sufficiently accurate for the majority of agricultural soils (Landon, 1991). Soil porosity (*p*) was calculated from the determined bulk density and particle density using the expression: $p = 1 - \rho_b/\rho_s$, where ρ_b and ρ_s are the soil bulk and particle densities (g/cm^3), respectively.

3.7 Determination of Soil Hydraulic Properties

3.7.1 Soil water content and soil water holding capacity

Soil water retention (SWR) in the lower suction range was volumetrically determined using a suction cell apparatus (Klute, 1986). The weighed saturated samples were taken into the tension table apparatus. The tension table was set at a suction of 0.1 kPa and the apparatus power was set on. The samples were left to equilibrate on the apparatus for three days. After equilibration the samples were taken out and weighed. The weights of equilibrated samples at 0.1 kPa were recorded. The samples were then returned and arranged on the apparatus and another suction value was set. A similar procedure was followed at suction values of 1, 10, 20 and 33 kPa. After these measurements, the same samples were placed in a pressure plate for measuring soil water retention corresponding to suction values of 50 kPa, 100 kPa and 1500 kPa respectively. A similar procedure to the tension table for water content determination was followed under the pressure plate apparatus. The samples were oven dried at 105^{0}C to constant weight and the oven dry weight of the samples determined. The volume of water retained from one suction value to another was obtained as the difference between the weight of the sample at respective suctions and the oven dry weight times the density of water (1 g/cm^3). Soil water retention for each suction was calculated as the ratio of the volume of water retained to the total volume of the soil (volume of core). Soil water retention at 33 kPa, and 1500 kPa were taken to represent field capacity (FC) and permanent wilting point (PWP) water contents, respectively. Available soil water capacity (AWC) was obtained as the difference between FC and PWP. The determined soil moisture retention was used to test the selected PTFs and in developing regression equations to correlate soil water retention with soil physical properties, namely percentage texture, organic carbon, bulk density and total porosity.

3.7.2 Soil saturated hydraulic conductivity determination from tension infiltrometer flow rates

Soil saturated hydraulic conductivity (K_s) was determined by using the proposed method of Reynolds and Elrick (1991) which is a modification of Wooding's solution for infiltration from a shallow pond. The proposed equation has the form given below:

$$Q_s = \left(\frac{a}{Gd} + \pi a^2\right) K_s \exp(\alpha\varphi) \qquad (16)$$

Where Q_s is the steady state flow rate (m^3/s) determined as a product of the cross-sectional area of tension infiltrometer reservoir and the steady state change in water flow levels, a is the disc radius (cm), Gd is the dimensionless shape factor for tension infiltration from the surface disc ($Gd = 0.25$, Reynolds and Elrick, 1991), α is the air entry value (cm^{-1}), K_s is the saturated hydraulic conductivity (cm/h) and φ is the tension setting for the infiltrometer (cm).

Transforming Equation 16 into logarithmic form becomes:

$$\ln Q_s = \alpha\psi \ln\left[\left(\frac{a}{Gd\alpha} + \pi a^2\right) K_s\right] \qquad (17)$$

When Equation (17) was plotted, it defined a straight relationship between ln Q_s and ψ and the value α was determined for each soil profile from the slope of the graph for equation (17) and is defined as

$$\alpha = \frac{\ln(Q_1 / Q_2))}{(\psi_1 - \psi_2)} \qquad (18)$$

Where Q_1 and Q_2 refer to steady state flow rates at two selected tensions. The K_s was determined from ln Q_s axis intercept defined by equation 19.

$$K_s = \frac{Gd\alpha Q_1}{a(1 + Gd\alpha\pi a)(Q_1 / Q_2)^p} \qquad (19)$$

Where $p = \psi_1/(\psi_1-\psi_2)$ and the subscripts 1 and 2 refer to the two selected tensions, respectively. The unsaturated hydraulic conductivity at a given tension ($K\psi$) for each soil profile was calculated using equation (20) given below:

$$K(\psi) = K_s e^{(\alpha\psi)} \qquad (20)$$

The accuracy of the results from the Tension infiltrometer were doubtful due to low K_s values for loamy sand, sandy loam and sand soils compared to clay soils. Flow rates in most cases is low for clay than sand because water infiltrates clay less than coarse textured soil (Campbell, 1985). These results were, therefore, thought unreliable in meeting the goal of this study and soil infiltration rates from the double ring infiltrometer were used for approximating K_s for the studied soils.

3.8 Determination of Soil Infiltration Rates Using the Double Ring Infiltrometer Data

Infiltration measurements were conducted between 26th of March to 5th of April 2001. This was during the start of the long rainy season. Two double ring infiltrometers of 50 cm diameter and 25 cm height were used. The following procedures were followed for collecting infiltration rates from the double ring infiltrometer (Bouwer, 1978, 1986):

1. A level soil surface was selected at a distance of three metres from one side of a dug profile. Plant and grass remains that might get caught under the cylinder edge when the device is inserted were removed;
2. A small circular excavation having a diameter larger than that of the double ring was made and the surface was prewetted with a sufficient amount of water. The prewetting was done twelve hours before the infiltration measurements were to be conducted. This allowed easier driving of the rings with little soil disturbance. When there was a sufficient amount of rainfall a day before the measurement then prewetting was assumed unnecessary;
3. The two concentric rings (inner and outer) were placed on the soil surface and pushed vertically downward. A piece of a flat wood was placed on top of the two rings and the rings were pushed down uniformly and straight. Gentle force was applied using a 0.5 kg hammer at the top center of the wood when small resistance was encountered in pushing the rings. Care was taken in avoiding soil disturbance. The double ring was driven into the soil up to a depth of at least 10 cm;
4. The rings were filled with water until when both rings had the same water level at the calibrated zero mark;
5. The stopwatch was started and the level of fall of water was recorded periodically using a tape attached on the inner ring of the double ring infiltrometer. During the infiltration process water was kept at the same level

manually by adding small amount of water in both rings to minimize lateral movement of water between the rings;

6. Infiltration measurements were done until a steady state infiltration rate was attained which was assumed to be at least three hours in this experiment. Three double ring infiltration measurements were taken for each profile. Similar procedures were followed in all the fourteen studied profiles.

Data obtained from the double ring infiltrometer were used to calculate the cumulative infiltration and cumulative time. Calculation of the cumulative infiltration, cumulative time and fitting of the equation from the cumulative infiltration data was done using the Microsoft Excel programme. These were used to plot the cumulative infiltration curve for each setting in a profile. Infiltration rates (mm/h) were obtained by differentiating fitted equation to cumulative infiltration data according to Jensen (1983) which is written as:

$$F = aT^{b} + C \qquad (21)$$

Where: F is the cumulative infiltration (mm), T is the intake time (h) from the start of infiltration, *a*, *b*, and *C* are constants (coefficients on fitted equation of the cumulative infiltration data). The resulting differentiated equation for calculating infiltration rates appears in the following form:

$$I = \frac{\partial(F)}{\partial t} = abT^{b-1} = kT^{n} \qquad (22)$$

Where *I* is the infiltration rate (mm/h), *k* is equal to *a*b*, and n is equal to *b*-1. The final steady state infiltration was used to estimate the saturated hydraulic conductivity for studied soils. The estimates of saturated hydraulic conductivity were obtained by the method of Youngs (1968) by multiplying the final steady state infiltration rates by a factor of 2/3. The estimated values of K_s (referred to as measured values in this work) from the double ring infiltrometer were then used in developing regression equations for estimating the K_s from the representative soil physical properties (RSPP), namely texture, bulk density, organic carbon and total porosity.

The RSPP were obtained from the total depths of the soil profiles and the depths of each horizon in a soil profile. The ratios of soil profile horizons depth to the total depth of the soil profile were determined for each horizon of the soil profile. The determined ratios were then multiplied with the percentages of soil particle size fractions, organic carbon, bulk density and total porosity for each horizon of the soil profile to obtain a fraction of each property contributing to the representative property of the soil profile. The summation of the obtained fractions from the percentages of soil particle size fractions, organic carbon, bulk density and total porosity for all the horizons of a soil profile was done to obtain the RSPP of the profile. Similar procedures were done for all the studied soil profiles. The RSPP were thought to be good indicators of the determined infiltration rates and K_s values because they were determined from non-homogeneous layered soils.

3.9 Evaluation of the Selected PTFs for Soil WRC and K_s

The selected PTFs for estimating soil MRC was evaluated using the collected soil texture data. This was done at matric potentials of 1, 10, 33, 100, 1500 kPa, and AWC. The evaluation was done by substituting obtained values of soil texture from the study area on the selected PTFs. The determined values were compared with measured values using scatter plots and by determining mean differences (MD), root of mean squared differences (RMSD) and the correlation coefficients (R) between measured and estimated values to see how much evaluated PTFs deviated from measured values. Calculated RSPP were used in evaluating the selected PTFs for K_s estimation. Similar comparison measures applied for testing soil WRC PTFs were followed for K_s PTFs.

The MD represents the expected value of model residuals, and it can be interpreted as an indicator of the model's tendency for over-or under-estimation (Tietje and Tapkenhinrichs, 1993; Schaap *et al.*, 1998; Imam *et al.*, 1999). The RMSD measures the ability of the predicted hydraulic parameter to match measured parameter and R indicates how well predicted hydraulic parameters matched the trends in measured parameters (Shaap *et al.* 1998). These measures of goodness of fit are defined by:

$MD = 1/n\Sigma_{i=1,n}(O_i-P_i)$

$RMSD = [1/n\Sigma_{i=1,n}(O_i-P_i)^2]^{1/2}$

$R=1/\sigma_o\sigma_p\Sigma_{i=1,n}(O_i-\mu_o)(P_i-\mu_p)$

Where, O_i is observed value, P_i is predicted value, n is sample size, μ_o, σ_o are mean and standard deviation of observed values, μ_p, σ_p are mean and standard deviation of model prediction.

3.10 Statistical Data Analysis

Data analysis was done using the Microsoft Excel 97 and Microsta programs. Multiple linear regression equations were developed relating the volumetric moisture contents at respective matric suction and measured K_s to representative soil physical properties. Best regression equation describing a larger variation (r^2) of soil MRC and K_s from the basic and representative soil physical properties were obtained using stepwise regression procedure at a probability of 0.001 for the remaining independent variables in the equation.

CHAPTER FOUR

4 RESULTS AND DISCUSSION

4.1 Physical Properties of the Soils in the Study Area

A total of fifty one (51) soil samples were studied. The soils used in the study consisted of thirty (30) samples of clay soils, five (5) samples of sandy clay, five (5) samples of sand clay loam soils, six (6) samples of loamy sand, one (1) sample of sandy loam and four (4) samples of sand soil. The detailed physical properties of the soil samples are given in Appendices 1 to 3. Clay and sand textures had the highest soil fractions compared to silt. There were small differences for the minimum and maximum obtained values of BD between the three textural fractions. Soil OC was very low for the studied soils with a decreasing trend with an increase in soil depth. Clay soils showed to have better water holding capacities compared to silt and sand although the differences of the retained soil moisture between sand and clay was small. Sand, loamy sand and sandy loam had the highest infiltration rates and clay soils had the lowest infiltration rates for the double ring infiltrometer. The infiltration and saturated hydraulic conductivity (K_s) rates increased with the increase in size of the soil fractions for the DR. Tension infiltrometer (TI) showed the soils to have very slow to slow K_s compared to DR determined values (Table 4.5 in section 4.1.7).

4.1.1 Soil texture

The texture classes of the studied soil are shown in Table 4.1. The texture ranges for the studied soils were 2 to 77% clay particles content, 1 to 15% silt particles content

Table 4.1. Soil physical properties in the study area

Profile No.	Soil sample & depth (cm)	Particle size distribution (%)			% OC	BD (g/cm^3)	Porosity (%)	Texture
		sand	silt	clay				
SFP 1	Ap 0-20	63	9	28	1.29	1.49	44	Sand Clay Loam (SCL)
	B21 20-44	42	6	52	0.67	1.23	54	Clay (C)
	B22 44-84	40	6	54	0.43	1.38	48	C
	B23 94-120	42	6	52	0.28	1.49	44	C
SFP 2	Ap 0-19	48	5	47	1.10	1.21	54	Sand Clay (SC)
	AB 19-54	24	6	70	0.74	1.18	55	C
	Bt1 54-94	28	7	65	0.51	1.26	53	C
	Bt2 94-132	28	8	64	0.35	1.31	51	C
SFP 3	Ap 0-10	49	6	45	0.90	1.42	46	SC
	A3 10-30	43	4	53	0.67	1.29	51	C
	B21 30-60	35	6	59	0.51	1.21	54	C
	B22 60-130	40	8	52	0.20	1.15	57	C
SFP 4	Ap 0-20	65	4	31	0.82	1.40	47	SCL
	AB 20-40	63	6	31	0.47	1.46	45	SCL
	Bcn? 40-70	57	6	37	0.47	1.59	40	SC
SFP 5	Ap 0-20	39	8	53	0.90	1.21	54	C
	B2120-40	35	11	54	0.67	1.13	57	C
	B22 40-70	30	6	64	1.25	1.19	55	C
	B23 70-150	28	11	61	0.35	1.11	58	C
SFP 6	Ap 0-16	28	8	64	1.49	1.20	55	C
	B21t 16-40	21	6	73	0.86	1.19	55	C
	B22t 40-90	19	4	77	0.47	1.20	55	C
	B23t 90-154	16	8	76	0.59	1.20	55	C
SFP 7	Ap 0-15	24	15	61	2.58	1.18	55	C
	B2 15-40	25	4	71	2.27	1.23	53	C
	B2g 40-130	28	4	68	1.86	1.45	45	C
SFP 8	Ap 0-30	48	6	46	1.76	1.27	52	SC
	Btg 30-105	28	8	54	0.90	1.45	45	C
SFP 9	Ap 0-19	68	6	26	1.17	1.39	48	SCL
	Bs? 19-40	38	11	51	0.82	1.58	40	C
	B21 40-62	87	4	9	0.24	1.58	40	Loamy sand (LS)
	B22 62-84	76	3	21	0.12	1.29	51	SCL
	Bwt 84-110	34	1	65	0.32	1.34	49	C
SFP 10	Ap 0-18	48	6	46	1.02	1.21	54	SC
	B2t1 18-110	34	3	63	0.32	1.02	61	C
	B2t2 110-140	34	3	63	0.16	1.19	55	C
SFP 11	Ap 0-10	45	8	47	1.45	1.23	54	C
	B21t 10-34	34	3	63	0.74	1.16	56	C
	B22t 34-70	27	6	67	0.47	1.21	54	C
	B23t 70-120	27	3	70	0.32	1.14	57	C
	B24t 120-153	23	6	71	0.28	1.16	56	C
SFP 12	Ap 0-35	82	9	9	0.35	1.38	48	LS
	B21 35-110	84	4	12	0.12	1.53	42	LS
	B22 110-140	84	5	11	0.08	1.59	40	LS
SFP 13	Ap 0-36	79	9	12	0.78	1.44	46	Sandy Loam (SL)
	BA 36-66	84	7	9	0.55	1.52	43	LS
	B 66-120	84	7	9	0.16	1.47	45	LS
SFP 14	Ah 0-25	89	7	4	0.59	1.26	53	Sand (S)
	Ab 25-55	93	2	5	0.24	1.39	47	S
	B21 55-94	96	2	2	0.12	1.56	41	S
	B22 94-150	96	2	2	0.08	1.59	40	S
Mean		48.67	6.06	45.08	0.70	1.32	50.21	
Stdev		24.15	2.69	23.53	0.56	0.15	5.81	

Stdev = standard deviation

and 16-96% sand particles. The percentage clay increased with soil depth in most of the studied soil profiles except in profiles 9, 12, 13 and 14. In profile 9 there were an alternating layers between sandy clay loam, loamy sand and clay and therefore the loamy sand underlying the clay layer had low clay content. The other last three profiles had mainly clay, which decreased or remained constant with the increase in soil depth. Percentage silt content showed no uniform trend with the variation in soil depth. It either increased or decreased with increase in soil depth. In some of the studied profiles percent silt content remained constant in all soil profile horizons. Percentage sand showed similar trends to silt except in the last three profiles where the percentage sand was relatively uniform (constant) with increase in soil depth.

4.1.2 Soil bulk density

Soil bulk density (BD) varied from 1.02 to 1.58 g/cm^3 for clay soils, 1.21 to 1.59 g/cm^3 for sandy clay soils, 1.29 to 1.49g/cm^3 for sandy clay loam soils, 1.26 to 1.59 g/cm^3 for sand soil, 1.38 to 1.59 g/cm^3 for loamy sand and 1.44 g/cm^3 for sandy loam. Eight percent of the studied topsoils had relatively high BD compared to subsoils BDs and eighty percent had BD that, either increased or decreased with the increase in depth of the soil profile. Similar values of BD have been reported by Kaaya (1989) from the SUA farm soils.

4.1.3 Soil organic matter content and total porosity

The soils had low to very low organic carbon content varying between 0.08 to 2.58 % (Table 4.1). Soil organic carbon decreased with increase in soil depth in all studied soil profiles. Total porosity of the soils varied between 40 to 61 % in general. It varied between 40 to 61% for clay soil, 40 to 54% for sand clay, 44 to 51% for sandy clay loam, 46 % for sandy loam, 40 to 48% for loamy sand and 40 to 53 % for sand soils. Generally total porosity was high for clay soils and variations were relatively uniform for the remaining soil types. The obtained values are within the given ranges by Landon (1991) for agricultural soils.

4.1.4 Soil moisture and available water holding capacity of the studied soils

The soil moisture holding capacity ranged between 6.8 to 44 % (cm^3cm^{-3}) at field capacity (FC), 1.4 to 32 % (cm^3cm^{-3}) at permanent wilting point (PWP) and the available water capacity (AWC) varied between 2.1 to 23 % (cm^3cm^{-3}). The maximum AWC capacity was relatively high for sand clay soil (23 cm^3cm^{-3}) and the remaining soil types had a relatively equal amount of maximum AWC. Table 4.2 shows a summary of the amount of moisture retained in percentage at FC, PWP and the AWC. Kaaya (1989) and Kapele (2000) reported ranges of 5.1 to 18.1 % and 5.8 to 16.6 % (cm^3cm^{-3}) of AWC from similar studied soils. Therefore, the obtained values are generally comparable to the reported findings. Detailed results for the measured soil water holding capacity are given in Table 2.2 of Appendix 2.

Table 4.2. Ranges of soil water holding capacities at field capacity (FC), permanent wilting point (PWP) and available water capacity (AWC) for studied soils

Soil type	FC				PWP				AWC			
	Mean	Stdev	Min	Max	Mean	Stdev	Min	Max	Mean	Stdev	Min	Max
C	30.11	5.45	21.33	43.24	24.40	3.69	17.59	31.55	5.64	2.98	2.14	15.19
SC	29.11	8.46	22.86	43.60	19.84	0.60	19.30	20.64	9.27	8.09	3.46	23.30
SCL	24.83	1.71	22.65	26.99	13.75	2.68	9.43	16.06	11.09	2.01	9.10	14.23
LS	14.53	3.36	12.35	21.22	5.91	0.63	5.41	6.75	8.62	3.60	6.04	15.81
SL	15.41	0	15.41	15.41	7.12	0	7.12	7.12	8.29	0	8.29	8.29
S	10.64	3.00	6.84	13.38	1.99	0.71	1.37	2.62	8.64	2.37	5.47	10.79

FC = field capacity, PWP = permanent wilting point, AWC = available water capacity, Max = maximum, Min = minimum.

4.1.5 Soil infiltration characteristics: Double ring infiltrometer results

The basic final soil infiltration rates for the soils were 23 to 37 mm/h for clay, 41 to 158 mm/h for sandy clay, 38 to 42 mm/h for sandy clay loam, 326 mm/h for sandy loam, 223 mm/h for loamy sand and 287 mm/h for sands (Table 4.3). According to Landon (1991) the basic infiltration rates were moderate for clay and sandy clay loam soils, moderate to rapid for sandy clay soils, very rapid for sandy loam and rapid to very rapid for loamy sand and sands. The soil basic infiltration rate was very high for sandy clay (Profile no.2) probably because the site was recently been cultivated with a rough plough and undecomposed grasses during measurements which could have resulted in water moving along the plough layer (lateral flow) from the double ring infiltrometer. The obtained basic soil infiltration rates are similar to those reported by Kongola (2000) for SC (except for soils of Profile number 2, which had too high infiltrations rates), Njovu (2000) for SCL and Nindi (1999) for SL, LS and S soils. Infiltration rates for clay soils were a bit lower compared to reported values by Njovu (2000) for similar soils probably because of the differences in soil structure, total porosity and the nature of clay particles obtained in the study. Generally obtained values were within the suggested ranges (Landon, 1991). Typical infiltration characteristic curves for the studied soils are given in Appendix 3.

Table 4.3. Basic final steady state infiltration rates using double ring infiltrometer

Profile site and number	Basic infiltration rate (mm/h)	Top soil texture
SFP1	42	SCL
SFP 2	158	SC
SFP 3	46	SC
SFP 4	112	SCL
SFP 5	33	C
SFP 6	23	C
SFP 7	23	C
SFP 8	30	C
SFP 9	38	SCL
SFP 10	41	C
SFP 11	37	C
SFP 12	223	LS
SFP 13	326	SL
SFP 14	287	S

4.1.6 Saturated hydraulic conductivity from double ring infiltrometer

Saturated hydraulic conductivity computed from the double ring infiltration rates varied from 15to 98 mm/h for clay soils, 25 to 79 mm/h for sandy clay loam soils, 149 to 217 mm/h for loamy sand and that for sand was 192 mm/h (Table 4.4). Saturated hydraulic conductivity was slow for clay soils, moderate to moderately rapid for sandy clay loam soils, and it was very rapid for loamy sand and sand soils (Landon, 1991). The K_s values for soil profile nine seem to be low compared to the soil textural class. This was probably due to the saturated clay sub soil horizon underlying the topsoil horizon.

Table 4.4. Representative soil physical properties and measured K_s for the studied soils

PF No.	RPSD			ROC	RBD	RP	K_s	RTC
	C (%)	Si (%)	Sa (%)	(%)	(g/cm^3)	(%)	(mm/h)	
SFP 1	52	6	42	0.56	1.28	44	28	C
SFP 2	64	7	29	0.61	1.25	53	98	C
SFP 3	53	7	40	0.40	1.21	55	31	C
SFP 4	34	5	61	0.57	1.50	44	79	SCL
SFP 5	59	10	31	0.64	1.13	56	22	C
SFP 6	75	6	19	0.69	1.20	55	15	C
SFP 7	68	5	27	2.02	1.38	48	15	C
SFP 8	52	7	41	1.15	1.40	47	20	C
SFP 9	36	5	59	0.50	1.43	46	25	SCL
SFP 10	61	3	36	0.38	1.08	59	27	C
SFP 11	67	5	29	0.49	1.17	56	25	C
SFP 12	11	5	84	0.17	1.50	43	149	LS
SFP 13	10	8	82	0.44	1.47	44	217	LS
SFP 14	3	3	94	0.21	1.49	44	192	S

RPSD = representative particle size distribution (%); ROC = representative organic carbon (%); RBD = representative bulk density (gcm^{-3}); RP = representative porosity (cm^{3}cm^{-3}); RTC = representative soil textural class; PF = Profile

Generally the K_s values were low for clay soils compared to sands except for soil Profile number 2 for the reasons explained in section 4.1.5. Therefore, the Profile No. 2 K_s value was not included in PTFs testing and in developing regression equation for K_s estimation because it was considered to be outside the range of expected values for the determined representative soil profile texture. There was no systematic variation in K_s with soil texture and total porosity (Table 4.4). The values of K_s increased or decreased with the decrease or increase in representative bulk density (RBD).

4.1.7 Hydraulic conductivity results from the Tension Infiltrometer

Table 4.5 below shows results for soil hydraulic conductivity from the studied soils determined using tension infiltrometer data. Saturated hydraulic conductivity varied from 1.18 to 13.93 mm/h that was very slow to slow (Landon, 1991). It was highest for sandy clay soils of Profile number 2 compared to other soils followed by clay soils of Profile number 8. The loamy sand, sandy loam and sand soils had the lowest values of K_s. Despite the generally low K_s values obtained from the tension infiltrometer data for the studied soils, high K_s values for sandy clay and clay compared to sandy soils are probably due to improper flow rates obtained from the tension infiltrometer.

Table 4.5. Hydraulic conductivity for the fourteen studied topsoil using tension infiltrometer

Profile	(α) (cm^{-1})	K_s (mm/h)	K(ψ) (mm/h)		
			5 cm tension	7 cm tension	10 cm tension
SFP1	0.22	5.23	1.74	1.12	0.58
SFP2	0.17	2.66	1.15	0.82	0.50
SFP3	0.33	13.93	2.72	1.41	0.53
SFP4	0.19	2.45	0.97	0.67	0.39
SFP5	0.17	2.74	1.20	0.88	0.52
SFP6	0.18	2.84	1.15	0.80	0.47
SFP7	0.24	8.37	2.59	1.62	0.80
SFP8	0.14	2.85	1.41	1.06	0.69
SFP9	0.14	3.65	1.81	1.37	0.90
SFP10	0.18	4.28	1.71	1.19	0.69
SFP11	0.21	6.26	2.15	1.40	0.74
SFP12	0.13	1.18	0.61	0.47	0.32
SFP13	0.17	1.79	0.78	0.56	0.34
SFP14	0.17	1.33	0.57	0.40	0.24

Unsaturated hydraulic conductivity (Kψ) was low compared to K_s as it was expected. This is because at saturation, flow is mainly due to gravity while under unsaturated conditions capilarity flow is a dominating factor. The values of Kψ

decreased with the increase in tension set on the infiltrometer. Similar trends in $K\psi$ variation at different tensions were reported by Lwegenzya (2001) on soils of the western part of the Uluguru Mountains and Bazguba (2001) on SUA farm soils using a similar instrument.

Saturated soil hydraulic conductivity, K_s values determined using tension infiltrometer (TI) were very low compared to those obtained from the double ring (DR) measurements in all studied soil profiles. There was no significant ($p > 0.05$) statistical correlation between the DR and TI determined K_s values. The reasons for the differences are probably due to inaccurate flow rates for the TI used to calculate K_s. However, presence of lateral flow, dead root channels, macropores, worm holes, and animal burrows may have significant effects on K_s as they contribute largely to the flow of water for the DR. On the other hand, these characteristics cannot have an effect on flow rates for the TI because of the applied tension and only micropores contribute to flow in this case.

The values of parameter α showed a similar trend to the obtained K_s values; being higher for soils with higher K_s values. The mean value of α for the topsoil textures of the studied soil was 0.19 cm^{-1}. Lwegenzya (2001) obtained an average value of 0.25 cm^{-1} for α for kaolinitic clay soils of the western parts of the Uluguru Mountains. Wang *et al.* (1998) found the parameter α to vary from 0.008 to about 0.15 cm^{-1} for fine textured soils such as clay and for coarse soils such as sand respectively. Average values of 0.02, 0.02, 0.04, 0.02 and 0.04 cm^{-1} for α for soil textures C, SC, S, SCL, SL, and LS respectively have been reported by Imam *et al.* (1999). Variation in α is probably caused by spatial soil heterogeneity in as much as soil hydraulic properties may change in a very short distance (Wang *et al.*, 1998). Vereecken (1988) reported sand fraction as an important soil property controlling the parameter α. The larger the sand fraction was, the bigger was the magnitude of α. Small values of α for sandy compared to clay soils are mainly due to inaccurate flow rates determined from the TI as was the case for the obtained K_s values. Therefore, the value of the parameter α varies with the soil type and within soils due to heterogeneity caused by different physical, chemical, and biological properties during soil formation.

Tension infiltrometers have been shown to give reliable estimates of hydraulic conductivity of different soils (White and Sully, 1987, Smethen and Clothier, 1989 Ankey *et al.*, 1991, Logsdon and Jaynes, 1993). However, measurements from tension infiltrometers may be adversely affected by small variations in experimental procedures (Close *et al.*, 1998). Studies by Close *et al.* (1998) on membrane-contact material for the tension infiltrometers using potassium iodide reveals major sources of variability in infiltration results and hence the hydraulic conductivity as being the failure to achieve complete contact between the tension infiltrometer membrane and the contact material.

Soil hydraulic conductivity is a variable property mainly due to spatial variability of soil properties. The initial soil moisture content before infiltration measurements can contribute to the spatial variability of these properties. Preliminary measurements during a wet spring indicated that K_s values from small-base infiltrometers were lower than during dry spring (Smethen and Clothier, 1989). Other reasons for variability of these properties in this study are probably due to errors of the instrument but the main reason is subtle.

Variability in results including low hydraulic conductivity for loamy sand, sandy loam and sand soils may mainly be attributed to improper contact between the infiltrometer membrane and the contact material. To minimize errors for tension infiltrometer measurements mainly due to incomplete contact between the membrane and the contact material, Close *et al.* (1998) have proposed a new procedure to be applied when doing infiltration tests using Tension infiltrometers.

For reliable estimates of soil hydraulic conductivity using tension infiltrometers a number of factors have to be considered. Among others are such as good contact between the infiltrometer membrane and the contact material, soil heterogeneity, size of tension infiltrometer disk and the initial moisture content of the soil. Due to the inaccuracy of the TI results only infiltration rates and saturated hydraulic conductivity results from the DR measurements will be referred to in this work.

4.2 Soil Water Retention: PTFs Evaluation Results

Estimated soil WRC for each soil profile horizon at determined matric potentials and comparison between measured and PTFs estimated soil WRC are as shown in Appendix (4). Equations 1, 4, 5 6 and 8 from Table 2.4 were used to estimate soil WRC for Tomasella and Hodnett (1998) PTFs. Table 4.6 shows a summary result for the evaluated PTFs. The retained moisture content shows a decreasing trend with the decrease in matric potentials. There were good estimates of soil WRC at 33 and 1500 kPa's (Figures 4.1 and 4.2). Estimated soil MRC at other matric potentials matched measured trends well except for AWC as shown in appendix 6. Generally soil MRC was either over-or under-estimated. Soil MRC was overestimated at matric potentials of 1 and 1500 kPa and underestimated in the remaining matric potentials.

Table 4.6. Estimated soil MRC by Tomasella and Hodnett (1998) PTFs at determined matric potentials

Matric potential (kPa)	Estimated soil moisture retention % (cm^3cm^{-3})		
	Minimum	Maximum	Average
1	25.35	45.51	37.07
10	11.53	38.55	27.38
33	5.71	38.16	24.60
100	4.64	32.83	21.05
1500	2.00	32.21	19.42
AWC	3.70	7.76	5.17

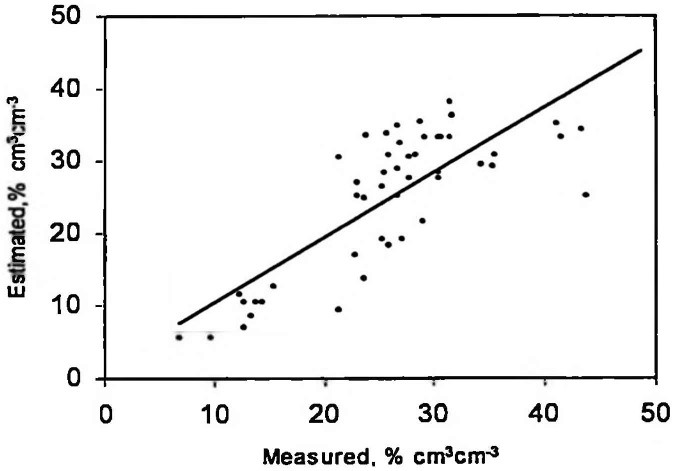

Figure 4.1. Measured volumetric soil water content versus those of Tomasella and Hodnett (1998) estimated values at 33 kPa matric potential

for the evaluated PTFs. The retained moisture content shows a decreasing trend with the decrease in matric potentials. There were good estimates of soil WRC at 33 and 1500 kPa's (Figures 4.1 and 4.2). Estimated soil MRC at other matric potentials matched measured trends well except for AWC as shown in appendix 6. Generally soil MRC was either over-or under-estimated. Soil MRC was overestimated at matric potentials of 1 and 1500 kPa and underestimated in the remaining matric potentials.

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10	11.53	38.55	27.38
33	5.71	38.16	24.60
100	4.64	32.83	21.05
1500	2.00	32.21	19.42
AWC	3.70	7.76	5.17

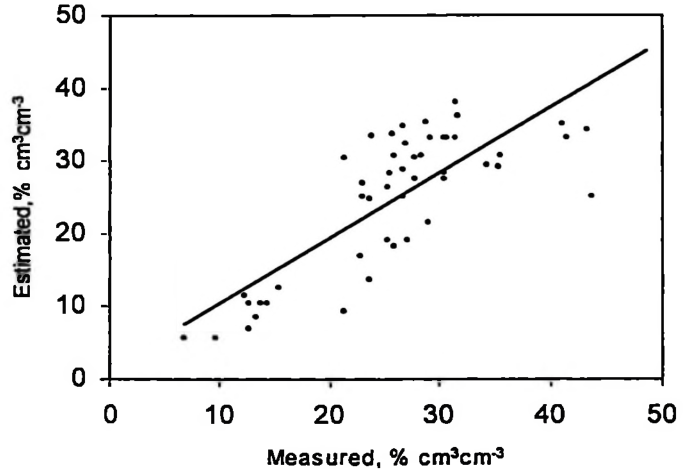

Figure 4.1. Measured volumetric soil water content versus those of Tomasella and Hodnett (1998) estimated values at 33 kPa matric potential

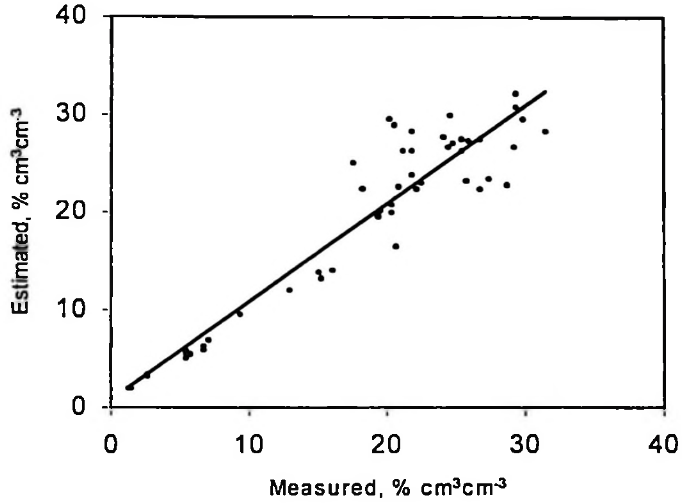

Figure 4.2 Measured volumetric soil water content versus those of Tomasella and Hodnett (1998) estimated values at 1500 kPa matric potential

The correlation coefficients between measured and estimated soil MRC were good except the correlation coefficient for AWC, which had a very small and negative correlation coefficient (Table 4.7). The low correlation for the AWC may be due to errors from the used estimation method because the AWC was obtained as the difference between FC and PWP equations for retained soil water content. Measurement errors for soil MRC values might also be the source of inaccuracies. The estimated soil water content increased with increase in percentage clay. No variation of soil water content was observed with the increase or decrease in percentage silt content probably because of low silt contents of the studied soils. The average mean difference (MD) and root of mean squared difference (RMSD) between measured and PTFs estimated soil water retention at selected matric potentials were not significantly different from zero.

Table 4.7. Mean differences (MD), RMSD and R between measured and estimated soil water contents by the tested PTFs at determined matric potentials

Matric potentials (kPa)	MD (cm^3cm^{-3})	RMSD (cm^3cm^{-3})	R
1	-0.05	0.07	0.83
10	0.02	0.05	0.82
33	0.02	0.06	0.79
100	0.02	0.05	0.81
1500	-0.01	0.04	0.94
AWC	0.02	0.05	-0.11
Mean	0.002	0.054	0.68

Differences between estimated and measured water contents might be due to the differences in soil texture used in developing the regression equation from those used in testing the models. Errors due to methods in collecting soil samples used for developing the equations are probably inclusive for the encountered differences. However, only soil texture (% clay and silt) was used in developing the equations for the Tomasella and Hodnett (1998) PTFs. The soil physical properties which have an influence on soil water retention such as bulk density and soil organic carbon were not included due to inconsistency of the properties from the data points used in developing the regression equations (Tomasella and Hodnett, 1998). Though the MD and RMSD between measured soil water retention values and those estimated using PTFs were small, the PTF cannot be regarded as good estimators of soil WRC due to cancellation of values for the MD. Generally good estimates of soil WRC were obtained at respective matric potentials considering the little soil information used in the tested PTFs equations. Therefore, PTFs developed from tropical soils can be used in estimating SHP for similar soils found in the tropics.

4.3 Developing PTFs for Soil WRC in the Study Area

4.3.1 Correlation coefficients between the soil physical properties in the developed regression equations

Table 4.8 shows the correlation coefficients for the independent variables used in developing regression equations for soil moisture retention estimation. There were high correlation coefficients, (r^2> 0.8) showing existence of multicollinearity between clay and sand and between bulk density and total porosity. The main reason for the multicolinearity is that sand is a linear combination of clay and silt, and total porosity is derived from the expression of bulk and particle densities. Use of either sand or porosity in developing regression equations could give similar results as when clay and bulk density have been considered. There was neither multicollinearity nor correlation for the silt and organic carbon content variables.

Table 4.8. Correlation coefficient (r) matrix for the independent variables used in the regression equations for soil MRC (values in parentheses indicate standard error)

Variable	Clay	Silt	Sand	OC	BD	Porosity
Clay	1.00	0.11 (.227)	-0.99 (.000)	0.34 (.009)	-0.68 (.000)	0.68 (.000)
Silt	0.11 (.227)	1.00	-0.23 (.058)	0.39 (.003)	-0.12 (.202)	0.12 (.198)
Sand	-0.99 (.000)	-0.23 (.058)	1.00	-0.37 (.004)	0.67 (.000)	-0.67 (.000)
OC	0.34 (.009)	0.39 (.003)	-0.37 (.004)	1.00	-0.21 (.068)	0.22 (.067)
BD	-0.68 (.000)	-0.12 (.202)	0.67 (.000)	-0.21 (.068)	1.00	-1.00
Porosity	0.68 (.000)	0.12 (.198)	-0.67 (.000)	0.22 (.067)	-1.00	1.00

4.3.2 Soil moisture retention estimated by soil physical properties at different matric potentials from the study area

Table 4.9 shows the correlation coefficients of SMR with different soil physical properties used in the study.

Table 4.9. Correlation coefficients of SMR with different soil physical properties

SMR (% cm^3cm^{-3})	Clay (%)	Silt (%)	Sand (%)	OC (%)	BD (g/cm^3)	Porosity (%)
SMR at 0.1kPa	0.57	0.10	-0.56	0.50	-0.50	0.50
SMR at 1 kPa	0.83	0.21	-0.84	0.57	-0.48	0.48
SMR at 10 kPa	0.81	0.21	-0.82	0.57	-0.44	0.44
SMR at 20 kPa	0.80	0.20	-0.81	0.58	-0.41	0.41
SMR at 33 kPa	0.79	0.21	-0.80	0.59	-0.38	0.38
SMR at 50 kPa	0.79	0.21	-0.81	0.59	-0.39	0.39
SMR at 100 kPa	0.80	0.20	-0.82	0.57	-0.40	0.40
SMR at 1500 kPa	0.94	0.20	-0.95	0.42	-0.49	0.49
SMR at AWC	0.36	0.01	0.35	0.32	-0.23	0.23

There were a highly significant ($p<0.001$) correlation of SMR with clay and sand at the determined matric potentials. There was a significant ($p<0.05$) correlation coefficient of the variable OC with SMR. The soil AWC shows small correlation with percent silt, sand and OC. No significant ($p>0.05$) correlation was observed between SMR and percentage porosity, silt and BD. The negative correlation of SMR with the soil physical properties indicates that increase in percentage sand for example, would result in decreased retained soil moisture and vise-versa for clay fractions. The correlation coefficients for clay and sand are equal and opposite showing multicollinear effects as explained in section 4.3 above. A similar phenomenon is shown for the variables BD and percentage porosity.

Regression equations for estimating soil moisture retention at determined matric potentials are shown in Table 4.10. Soil moisture retention at 0.1, 1 kPa and AWC was explained well by clay and organic carbon content. Soil moisture retention at other determined matric potentials were explained well using percentage clay, organic carbon and bulk density. Percentage silt had insignificant contribution for most developed equations except for the regression equation estimating soil WRC at 1500 kPa. This was probably due to low content of silt in the studied soils (1-15 %). These variables were highly correlated ($p < 0.05$) with the soil moisture retention at the respective matric potentials in both regression equations.

Table 4.10. Coefficients of multiple linear regression equations predicting volumetric water content (% cm^3cm^{-3}) as a function of texture, OC, and BD for selected matric potentials (values in parentheses indicate the standard error)

Eq. No.	Matric potential, kPa	Intercept	Clay, %	Silt, %	OC, %	BD (g/cm^3)	R
1	0.1	35.22	0.10 (0.025)		3.09 (1.028)		0.66
2	1	16.19	0.27 (0.027)		5.03(1.120)		0.89
3	10	-4.37	0.32 (0.037)		5.16 (1.139)	11.84 (5.335)	0.89
4	20	-8.76	0.32 (0.036)		5.36 (1.132)	13.59 (5.304)	0.88
5	33	-12.33	0.31 (0.036)		5.52 (1.120)	15.33 (5.249)	0.88
6	50	-12.62	0.31 (0.035)		5.37 (1.099)	15.06 (5.150)	0.89
7	100	-13.35	0.31 (0.034)		5.01 (1.069)	14.38 (5.010)	0.89
8	1500	-23.60	0.41 (0.019)	0.03(0.129)	1.25 (0.651)	16.15 (2.833)	0.97
9	AWC	8.75	-0.09 0.021)		3.59 (0.891)		0.60

The overall analysis of variance showed that the independent variables included in equations for particular matric potentials significantly ($p<0.05$) correlated to soil moisture retention. Figures (4.3) to (4.5) show scatter plots of laboratory measured values of water content at 33 kPa, 1500 kPa and at AWC versus those predicted using Equations 5, 8 and 9 in Table 4.10. There is a good agreement between the measured and estimated water content at 33 kPa and 1500 kPa. Although there is a tendency of either overestimating or underestimating the water content in both matric potentials, the points for the measured against predicted soil water contents lie consistently above or below a linear fitted line indicating a good agreement between the measured and estimated water content. Figure 4.5 shows a tendency of overestimating the soil AWC. Generally the water contents was overestimated at an average of 52% and underestimated at an average of 48% by the regression equations at the respective determined matric potentials. More results are given in Appendix 5 and 7.

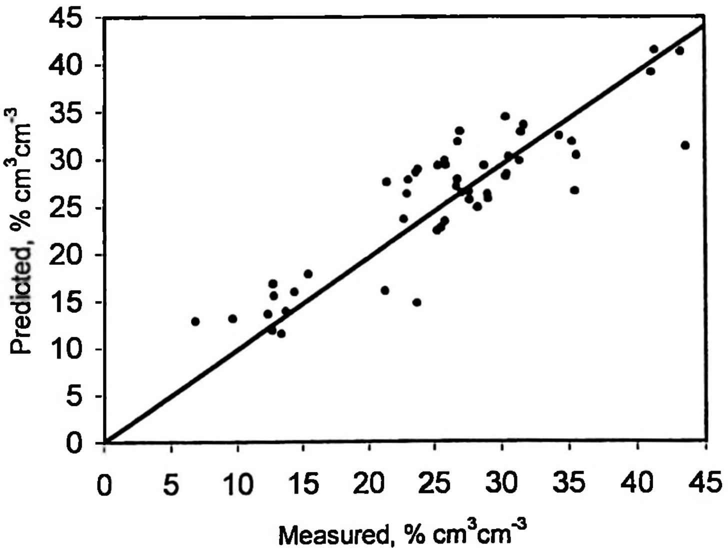

Figure 4.3. Measured volumetric soil water content versus those predicted values at 33 kPa using Eq. (5) in Table (4.10).

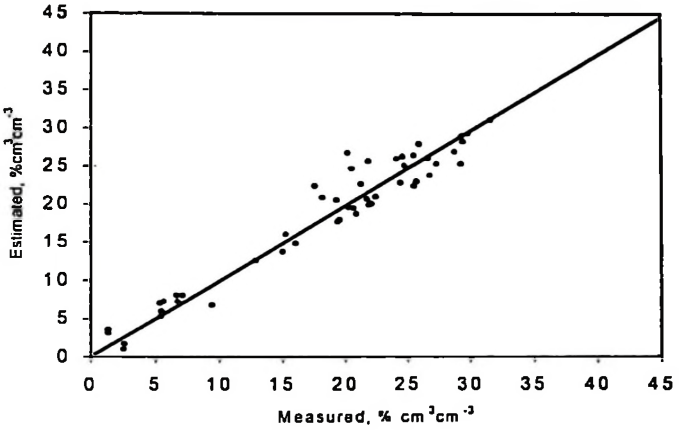

Figure 4.4. Measured volumetric soil water content versus those predicted values at 1500 kPa using Eq. (8) in Table (4.10)

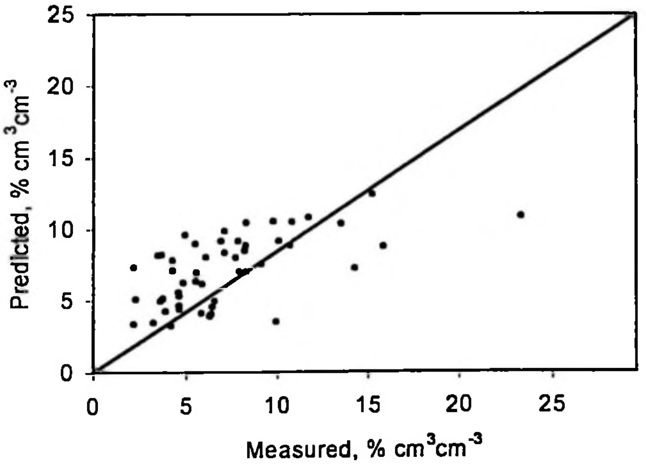

Figure 4.5. Measured available soil water capacity (AWC) versus those predicted using equation (9) in Table (4.10)

Over the six-predictor variables only sand and total porosity were not included in the equations for the reasons explained in section 4.3.1. The retained soil moisture at selected matric potentials was observed to increase with the increase in clay content and soil organic carbon. Also retained soil moisture content was observed to increase with decrease in BD. Silva *et al.* (1997) found that water retention characteristics (WRC) were related to clay, OC and BD.

Water retained at different matric suctions increased with increasing clay content. Similar findings were reported by van den Berg *et al.* (1997). Clay soils can hold a significant amount of water because of the relatively large surface areas of individual clay particles and the large number of very small pores. Clay acts as a binding agent between soil particles, it gives soil elasticity and provides cohesion of soil particles resulting into a network of capillary pores that hold moisture against the force of gravity. Percentage clay accounted for more than 60% in variation of SMR except at 0.1 kPa. There was a significant ($p < 0.05$) contribution of clay to the moisture retention in all the regression equation for the determined matric potentials.

The percentage OC had significant ($p \leq 0.04$) contribution to the regression equations for soil moisture retention at all the matric potentials except at 1500 kPa. Addition of OC to the regression equation increased the coefficient of determination to more than 70% in both determined soil MRCs except for soil MRC at 1 kPa. The retained soil water content for the topsoils was more a characteristic of OC than clay because percentage clay for the topsoil was relatively low than the sub-soil percent clay. Findings by Kay *et al.* (1997) have shown that an increase in the OC content of 0.01 kg/kg increases the available water content from 0.02 to 0.04 m^3m^{-3} with the largest increase occurring in coarser-textured soils. This resulted also in a decrease of the air-filled porosity at field capacity from 0.01 to 0.04 m^3m^{-3} with the largest decrease occurring in the finer textured soils. The effect of OC on water retention, especially at low matric potentials, has been recognized by several authors (Salter and Williams, 1965b, Pidgeon, 1972, De Jong and Loebel, 1982). Van den Berg *et al.* (1997) found that OC had little effect on soil WRC. The reasons for the little effect were the low OC content, and the well drained and strongly weathered soils used in their study. Despite the low OC content in this study, it was an important parameter in explaining the amount of water retained at different matric potentials because of its water holding nature as far as SWR is concerned.

The contribution of BD to the regression equations at 0.1, 1 kPa and AWC was not significant ($p>0.05$) and, therefore, not included in the equations for the respective matric potentials. For the remaining matric potentials there was a significant ($p < 0.05$) contribution of BD in determining soil moisture retention. Estimated soil water content by the regression equations increased with the decrease in BD in all determined matric potentials although the equations show that BD is positively correlated with soil water retention. Soils with low bulk densities retain more water than soils with a higher bulk density (van den Berg *et al.*, 1997). The increase in BD is associated with the decrease in number of water filled pores. The amount of water that can be retained at a given suction also depends primarily on the available pore space among other factors and, therefore, soils with low BDs are generally considered to be better structured, having sufficient amount of pore spaces than soils with high BD (van den Berg *et al.*, 1997).

Estimate of AWC was inferior though it was significant ($p<0.05$). Batjes (1996) and van den Berg *et al.* (1997) suggested that predicting AWC is most accurate when direct correlation is done between the differences in measured moisture content at FC and PWP and easily measured soil physical properties. The obtained results from this study show that there is no improvement when direct correlation between the differences in measured moisture content at FC and PWP and soil physical properties is done. The main reason for this might be due to the assumptions for the values taken to represent FC and PWP water contents. The approach used for determining AWC might also be the source of errors for the obtained results.

The efficiency of prediction by the regression equations for soil MRC increased with the increase in matric suctions (Table 4.10). Best estimate of retained soil water content was obtained at 1500 kPa matric suction as shown by high correlation coefficient. Use of measured soil MRC at FC and PWP as one of the independent variables can increase estimates of retained volumetric water contents at different matric potentials (Rawls *et al.*, 1982; Vereecken, 1988; Vereecken *et al.*, 1992; Vereecken, 1995). Rawls *et al.* (1982) found that including the moisture retained at FC and PWP increased the correlation coefficients significantly. This trial was not performed in the current study to see if the findings could support those of the other studies because SMR were estimated at a reasonable accuracy in the current study.

Generally there was a good agreement between the measured and predicted values of soil water contents at the selected matric potentials. Variables used in developing regression equations to predict moisture retention contributed significantly ($p<0.05$) in all matric potentials except for OC at PWP. This is probably due to the fact that the retained soil water contents at lower matric potentials is more related to soil texture than other properties. Correlation coefficients were high in most of the developed regression equations and, therefore, sufficient estimates of water contents at respective matric potentials could be obtained using the equations for soils with similar properties used in developing the regression equations.

Table 4.11 shows the MD, RMSDs, R, coefficients of variations and standard deviation between the measured and predicted soil moisture retention using the developed regression equations. The mean differences indicate that water contents estimated using regression equation was not far above or below the measured water contents. There were high correlation coefficients between the measured and predicted soil moisture retention compared to those obtained between measured and estimated by the PTFs of Tomasella and Hodnett (1998).

Table 4.11. Mean differences (MD), RMSD, R, CV and standard deviation (STDEV) between measured and predicted soil moisture retention at respective matric potentials

MP	MD and RMSD		R	CV (%)		STDEV (%)	
	MD	RMSD		Measured	Predicted	Measured	Predicted
0.1	-0.06	0.07	0.66	11.79	7.75	4.91	3.23
1	-0.06	0.07	0.83	27.27	22.65	8.66	7.19
10	0.02	0.05	0.89	29.96	26.51	8.71	7.70
20	0.02	0.06	0.88	31.83	28.12	8.60	7.59
33	0.02	0.06	0.88	32.95	29.08	8.49	7.49
50	0.02	0.06	0.89	33.66	29.80	8.42	7.50
100	0.02	0.05	0.89	35.84	31.82	8.28	7.35
1500	0.01	0.03	0.97	46.57	45.13	8.63	8.36
AWC	0.01	0.04	0.60	55.47	33.03	3.99	2.24
Mean	0.001	0.06	0.83	33.93	28.21	7.63	6.52

MP (kPa) is the matric potential.

The obtained MD and RMSD are within values obtained by Tomasella and Hodnett (1998), Tomasella *et al.* (2000) and Tietje and Tapkenhinrichs (1993). This indicates that predicted soil water retention by the developed regression equations were close to measured values. Reasons for the small differences between measured and predict soil MRC may be due to experimental errors in measurements of water contents at respective matric potentials. The developed equations can be used to estimate soil moisture retention for soils with similar physical properties to those used in developing the equations. Small sample size used in developing the equations is the main limitation when applied to areas outside the SUA farm.

4.4 Saturated Hydraulic Conductivity

4.4.1 Estimated K_s from some evaluated PTFs

PTFs of Ahuja *et al* (1984)

Estimated values of K_s didn't match measured values (Table 4.12 and Fig. 4.6).

Table 4.12. Estimated K_s values from different evaluated PTFs

PF.	Representative profile values						K_{sm}	PTFs estimated K_s (mm/h)			
NO	Cl (%)	Si (%)	Sa (%)	OC (%)	BD (g/cm^3)	P (%)	(mm/h)	A	C	V	J
1	52	6	42	0.56	1.28	44	28	31	7	15	158
3	64	7	29	0.61	1.21	55	31	57	10	27	260
4	53	7	40	0.40	1.50	44	75	31	2	2	23
5	34	5	61	0.57	1.13	56	22	53	20	47	369
6	59	10	31	0.64	1.20	55	15	43	4	28	201
7	75	6	19	0.69	1.38	48	15	12	0.3	4	39
8	68	5	27	2.02	1.40	47	20	18	0.9	4	33
9	52	7	41	1.15	1.43	46	25	33	3	4	48
10	36	5	59	0.50	1.08	59	27	56	52	73	1433
11	61	3	36	0.38	1.17	56	25	56	10	34	396
12	67	5	29	0.49	1.50	43	149	56	28	8	70
13	11	5	84	0.17	1.47	44	217	57	31	9	84
14	10	8	82	0.44	1.49	44	192	63	104	28	605

A = Ahuja *et al.* (1984), C = Campbell (1985), V = Vereecken *et al.* (1990), and J = Jabro (1992) PTFs, K_{sm} = measured K_s

Variations of estimated K_s are unsystematic. There is no clear trend in variation of K_s with the changes in fraction of the soil texture, BD, OC and total porosity. The K_s values are underestimated in six soil profiles and overestimated in seven remaining studied soil profiles. The mean error (MD = 44 mm/h) shows that K_s values are underestimated by the PTF of Ahuja *et al.* (1984).

Because of the small number (14) (Table 4.4) of data points only one value of the constants C and m were calculated for both representative soil textures (C, SCL, LS and S). The constants are determined from the fitted equation for K_s and effective porosity curve. The values are 188.74 mm/h and 1.01 for C and m respectively (Fig. 4.7, C = 188.74, m = 1.01). The parameters C and m have been found to vary for different soil textures (Ahuja *et al.*, 1984; Minasny and McBratney, 2000). Ahuja *et al.* (1989) found that C=7645 mm/h and m=3.29 (n= 473) for nine soil types in the USA. Several authors also found C to vary between 440 and 34,000 and m to vary between 1.59 and 3.98 (Rawls *et al.*, 1998). The obtained values in this study are small compared to other findings probably because of variation in soil types and small data points used. They represent general values for general soil textural classification, which could not be the case for specific soil textures. The representative soil properties for the profile not representing the actual textural fractions of profile horizons might have significant contribution to obtained values of the constants.

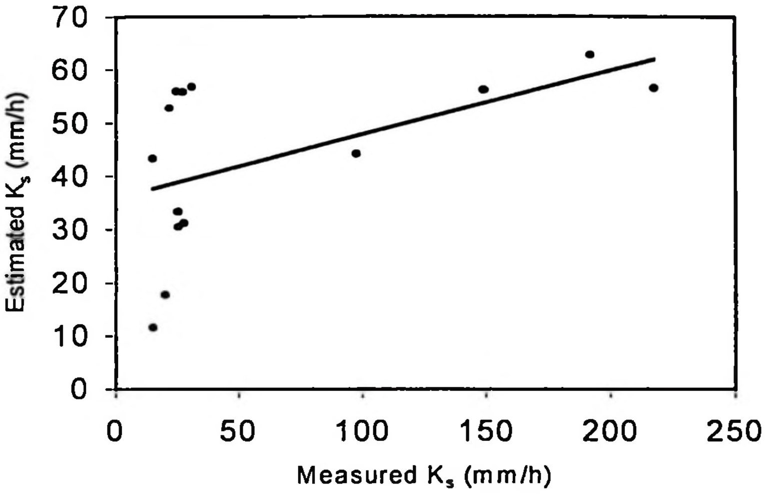

Figure 4.6. Measured K$_s$ versus those estimated using PTFs of Ahuja *et al.* (1984)

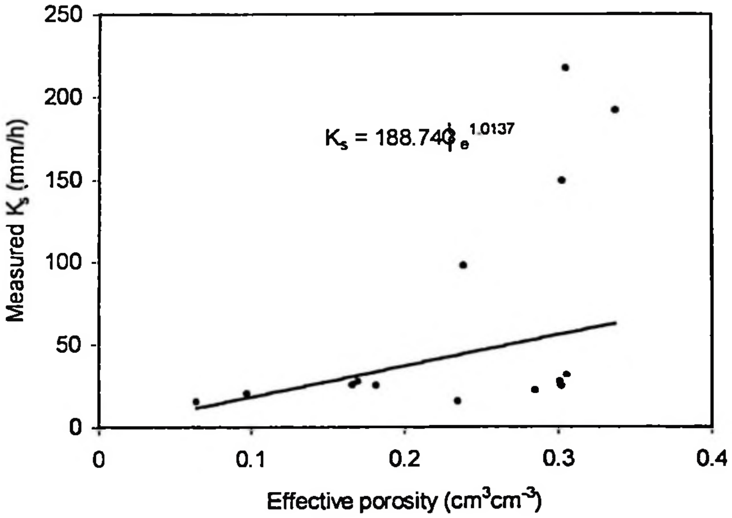

Figure 4.7. Effective porosity versus measured K$_s$ for the PTFs of Ahuja *et al.* (1984)

PTFs of Campell (1985), Vereecken *et al.* (1990), and Jabro (1992)

In the current study the PTFs of Campbell (1985) underestimated most of K_s. Obtained values showed that K_s values are underestimated in all the studied soil profiles. Estimated K_s values decreased with the increase in percentage clay and increased with the increase in percentage sand (Table 4.12 above and Fig. 4.8). Tietje and Hennings (1996) found the Campbell (1985) PTFs to perform better for sands. Similar under-estimation has been reported by Gowing and Young (1996) and Young *et al.* (1999) on similar soils from the study area. The radical underestimation of K_s suggests that a large part of disagreement may be due to the aggregation of clay particles (Gowing and Young, 1996). Representative soil profiles used to estimate K_s values for the PTFs might have led to the underestimation of K_s

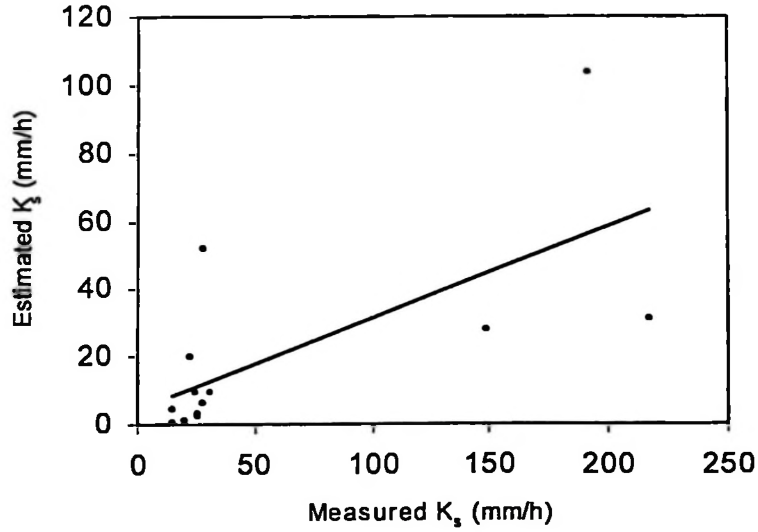

Figure 4.8. Measured K_s versus those estimated using Campbell (1985) PTFs

The estimated values of K_s using PTFs of Vereecken *et al.* (1990) are underestimated in most of the studied soil profiles except for the soil profiles 5, 6, 10 and 11 (Table

4.12 and Fig. 4.9). These are the profiles, which had higher percentage clay fraction. There is no systematic variation of the estimated values of K_s with the variables, percentage clay, silt, OC and BD. Tietje and Hennings (1996) reported larger estimation by the PTFs of Vereecken *et al.* (1990). These differences in findings are due to the differences in soil physical, chemical and mineralogical properties between tropical and temperate soils. High percentage organic matter, clay and silt contents are common characteristics of temperate compared to tropical soils, this result in increase of K_s due to increase in total porosity. Representative soil physical properties used in the study might have contribution to the differences as well.

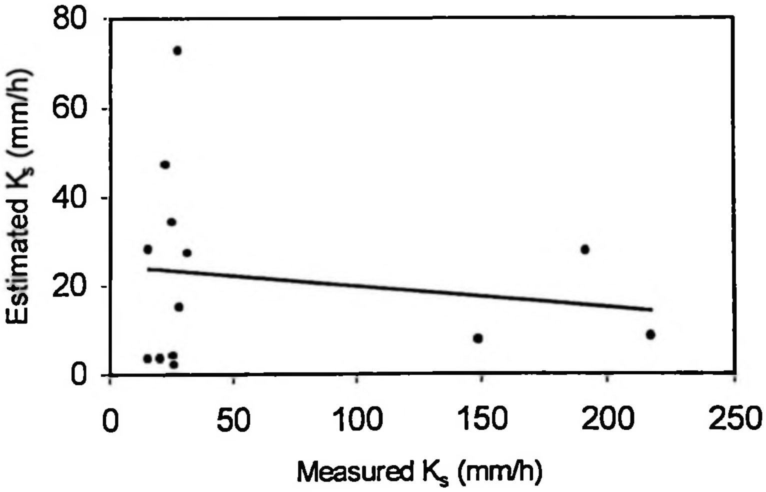

Figure 4.9. Measured K_s versus those estimated using Vereecken *et al.* (1990) PTFs

There was overestimated of K_s by the PTFs of Jabro (1992) in most the studied profiles, with no clear trend of the estimated values with respect to percentage clay, silt and BD (Table 4.12 and Fig. 4.10). Figure 4.10 shows to have a constant fitted line, this is due to very small measured K_s compared to PTF estimated values. The K_s values were overestimated with MD of 286 in magnitude. Overestimation's increased with increases in both the percentage clay and sand.

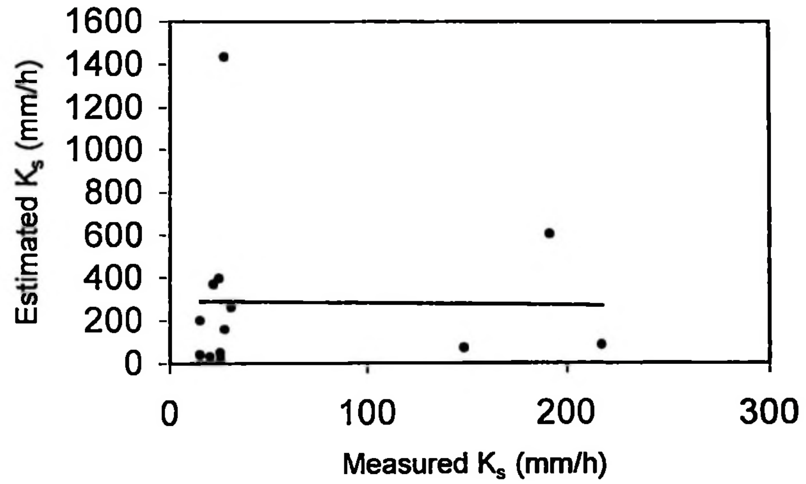

Figure 4.10. Measured K_s versus those estimated using Jabro (1992) PTFs

The evaluated PTFs either under-or-overestimated K_s values. However, there were a significant ($p<0.05$) correlation coefficients ($r = 0.67$) between measured and estimated K_s using the PTFs of Ahuja *et al.* (1984) and Campbell (1985). No significant ($p>0.05$) correlation coefficients ($r = -0.17, -0.02$) between measured and estimated K_s using Vereecken *et al.* (1990) and Jabro (1992) PTFs were observed. Variation between tropical and temperate soil types where the four tested PTFs for K_s estimation were developed, aggregation of clay particles, and methods used in measuring K_s have been identified as the source of differences between estimated and measured K_s among others in the current study. The computed weighted profile characteristics (representative soil physical properties) may also be the source of errors for the obtained results as clearly pointed out in the above sections.

The Differences between measured K_s values and those estimated using PTFs are also attributed to the differences in methods used in measuring K_s for developing the PTFs. Different methods and volumes in the measurement of K_s can produce unreliable results when applied to different soil types (Minasny and McBratney, 2000). Generally, PTFs for K_s estimation developed from the temperate soils are inaccurate and erratic and this shows the need of developing new PTFs to suit particular soil physical properties.

4.4.2 Development of an equation for predicting K_s

The independent variables used in developing the regression equation were correlated with the dependent variable for the identification of variables, which had a significant correlation with K_s. The variables were then transformed into logarithmic (log) and natural log (ln) except for the percentage OC because it had low values and the variables were correlated with log K_s and ln K_s. Table 4.13 shows the correlation coefficients between the independent variables and K_s for non-transformed and the transformed variables.

Table 4.13. Correlation coefficients for non transformed and logarithmic transformed K_s (mm/h) with soil physical properties

Variable	% C	% Si	% Sa	% OC	BD (gcm^{-3})	% p	K_s (mm/h)
Non-transformed	-0.81	-0.12	0.81	-0.43	0.55	-0.47	1.00
log transformed	-0.91	-0.25	0.90	-0.56	0.64	-0.61	1.00
ln transformed	-0.83	-0.19	0.73	-0.53	0.48	-0.44	1.00

The K_s was negatively correlated to percentage clay, OC, total porosity and positively correlated to percentage sand and BD both for non-transformed and transformed forms. No significant correlation coefficient was observed between percentage silt and K_s. The log transformed independent variables showed the highest correlation coefficients with K_s compared to non-transformed and natural log transformed variables. This is because K_s is assumed to be a log normally distributed random variable (Soil survey, 1993; Tietje and Hennings, 1996).

The correlation coefficients between K_s and the percentage clay and sand are highly significant ($p < 0.01$) for both non-transformed and transformed variables. There were also significant ($p < 0.05$) correlation coefficients between K_s and the remaining independent variables except for percentage silt.

Table 4.14 shows the coefficients of the developed regression equation for K_s prediction with similar variables both non-transformed and transformed. The variables logarithmic percentage of clay, silt, logarithmic BD and percentage OC were found to give the best prediction of K_s for the developed regression equation compared to non-transformed and natural-log transformed variables. The log percentage clay explained the largest (54.67 %) variation in K_s followed by the variable OC (23.29 %). In total, 95.23 % variations in K_s are explained by the variables.

Table 4.14. Coefficients of the regression equation for K_s estimation developed from the representative soil physical properties

Variable	Reg. Coeff.	STD. Error	T (DF=8)	Prob.	STD. Error of estimate.	R
Un-transformed						
C %	-3.52	1.56	-2.25	0.051		
Si %	1.84	7.65	0.24	0.815	48.23	0.82
OC %	20.98	49.47	0.42	0.682		
BD (g/cm^3)	-172.17	216.74	-0.79	0.447		
Constant	426.13					
log transformed						
log %C	-0.70	0.23	-3.11	0.015		
log %Si	0.31	0.38	0.82	0.436	0.17	0.94
% OC	-0.22	0.14	-1.56	0.158		
log BD	1.46	1.59	0.92	0.385		
Constant	2.40					
ln transformed						
ln C (%)	-0.88	0.32	-2.76	0.022		
ln Si (%)	0.57	0.54	1.06	0.316	0.57	0.87
OC (%)	-0.34	0.45	-0.75	0.471		
ln BD (g/cm^3)	-0.77	2.27	-0.34	0.743		
Constant	6.24					

Estimated values of K_s do not show a systematic variation with representative percentage clay, silt, sand and total porosity. The values of K_s either increased or decreased with the decrease or increase in representative BD. The percentage OC had a negative contribution on predicted K_s probably because of the more water holding nature than contributing to total flow though they have an effect on soil structure and hence total porosity.

Analysis of variance indicated that there was a significant ($p<0.05$) correlation between the estimated K_s and the independent variables. Only % clay had a significant ($p=0.015$) contribution to the regression equation. Hydraulic conductivity was closely related to clay content and its mineralogical composition in alluvial, red laterite and black soils (Sankaram, 1980). The reason for the other variables being not significant is that variables such as sand and porosity are derived from silt, clay and bulk density and, therefore, when included in the equation they do not add any extra information. This is indicated by the high correlation coefficients between percentage clay and sand and between bulk density and percentage total porosity. Therefore, when both the highly correlated independent variables are included in the equation result into insignificant contribution of the variable though the r-value may be high.

Figure 4.11. Shows a scatter plot for the measured and predicted values of K_s by the developed equation (log transformed coefficients in Table 4.14). Predicted K_s was either slightly under or over estimated. On average calculated K_s was underestimated with MD of 7.14×10^{-5} mm/h and RMSD of 0.198152. The obtained values of MD and RMSD are comparable to other reported finding (Minasny and McBratney, 2000).

Saturated hydraulic conductivity is a highly variable soil physical property. It varies widely both spatially and temporally in response to differences in land use (Mbangwu, 1987 as cited by Mbangwu, 1995; Minasny and McBratney, 2000). Measured values may easily vary by 10 fold or more for a particular soil series (Soil survey Manual, 1993). The values of K_s vary widely ranging from <0.025 mm/h in the least permeable to >250 mm/h in the most permeable soils (Sankaram, 1980).

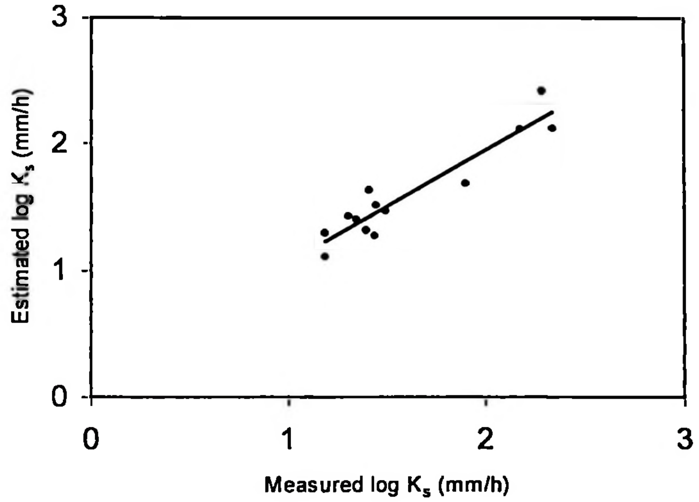

Figure 4.11. Measured K_s versus those predicted by the developed regression equation from Table (4.14)

Saturated hydraulic conductivity is influenced by the porosity of the soil, which in turn is affected by bulk density, structure, exchangeable ions of sodium, calcium, and potassium (Mbangwu *et al.*, 1983). Large continuous pores have lower resistance to flow (thus higher conductivity) than small or discontinuous pores (Soil Survey Manual, 1993). Soils with high clay content generally have lower hydraulic conductivity than sandy soils because the pore size distribution in sandy soils favors continuous flow even though sand soils have higher bulk densities and lower total porosity (total pore space) than clayey soil.

Mbangwu (1995) found that high bulk density reduces K_s by decreasing drainable porosity through compaction at the soil surface and consolidation in the sub soil. Increase in soil BD due to soil compaction result from decreases in the volume size, and shape of the soil conducting pores, which in turn results in the reduction of the soil macroporosity. Decrease in soil macroporosity is accompanied by high tortuosity of water flow. Both decrease in soil macroporosity as well as high tortuosity of water flow result in the reduction of soil water infiltration rate which, in turn, results into the reduction of soil hydraulic conductivity (Natai, 1997). The effects of BD and total porosity on K_s are highly interconnected such that effect on BD has an opposite effect on total porosity as far as K_s is concerned. Total porosity for the studied soils is higher for clay soils compared to sand soils but K_s values for clay soils are lower compared to sand soils. This confirms the reported findings on the effect of porosity on K_s. Similarly the effect of BD shows a similar trend of decrease in K_s with the increase in BD as reported by other findings above. Effects of BD on K_s have also been reported by Rawls *et al.* (1982).

Although it is understood that soils with finer materials will exhibit a gradual decrease of K_s, Vereecken (1988) found that K_s (measured or estimated) is not influenced by the soil texture. This finding can be scientifically explained that soil texture *per se* is not an attribute of soil structure, but the arrangement of the textural elements with the corresponding pore spaces determines soil structure, which has a remarkable influence on hydraulic conductivity. The hydraulic conductivity is obviously affected by structure as well as by texture, being greater if the soil is highly porous, fractured, or aggregated than if it is tightly compacted and dense (Hillel, 1971). The influence of soil texture on K_s does not show a particular trend for the studied soils, but, generally coarser soil texture have higher values of K_s except for the few cases of finer textured soils which can be attributable to factors such as lateral flow, potholes, presence of dead root channels etc. Cracks, worm holes and decayed root channels in the field may affect flow in different ways, depending on the direction and condition of the flow process. If the pressure head in the water is positive, these passages will run full of water and contribute greatly to the observed flux and measured conductivity (Hillel, 1971).

Because of various chemical, physical and biological processes, the hydraulic conductivity may change as water enters and flows in a soil as a result of changes occurring in the composition of the exchangeable ion complex due to differences in concentration of solutes in water entering the soil (Hillel, 1971). The aspects of exchangeable cations was not looked at to quantify their effects in this study and therefore, little or nothing can be explained on the extent of their effects on determined K_s values.

Factors such as water content and degree of wetness during the measurement of K_s might also have an influence in obtaining better estimates of K_s. A decrease in initial soil moisture content will result in a decrease in hydraulic conductivity due to an increase in flow resistance. This increase in flow resistance is a result of the increase of the contact surface per unit of soil liquid (Vereecken, 1988).

Methods of measurements, presence of lateral flow, potholes, cracks, decayed root channels and the methodology of finding weighted profile physical parameters are the main source of errors for the differences between the measured and predicted K_s values. The computed representative soil physical properties might not be representing the exact soil horizon, which could be used in determining the K_s of the soil profile. However, the developed regression equation shows a high accuracy (slope between measured and estimated $K_s = 1$) for predicting K_s and, therefore can be used for soils with similar soil physical properties. Small data points used in the study is the main limitation for the developed equation. Obtained values of measured and estimated K_s have implications for the different uses of soils. For irrigation scheduling purpose, large irrigation intervals and longer duration of irrigation will be required for soils with low values of K_s whereas for high values of K_s imply small irrigation intervals and shorter duration of irrigation. Similarly, the underground flow of chemicals will be high for soils with high K_s values compared to soils with low K_s values.

Generally, over-or under-estimation of soil hydraulic properties by PTFs when tested on different soils from similar environment has been reported (Tietje and Hennings, 1996). The results from the current study indicate that reliable estimates of soil hydraulic properties using PTFs can be obtained when applied to similar soil properties from similar environmental conditions. This is the main limitation for development of universal PTFs applicable for different soils from different environmental conditions.

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

Despite the recognized importance of soil hydraulic properties, there are no in-depth studies that have been done to characterize these properties under SUA farm soils. Most studies that have been done on the SUA farm have dealt with soil survey for rain-fed agriculture, erosion mapping and predictions, and on physical, chemical and mineralogical studies. This study looked into the possibility of using the existing models developed from both temperate and tropical soils and developing simpler models for the estimation of soil hydraulic properties. The PTFs developed from temperate soils especially the tested PTFs for K_s estimation produced unreliable and erratic results. The tested PTFs for SWR that were developed from tropical soils produced plausible results. Good prediction with high r-values of soil WRC and K_s were obtained by the developed simple regression equations from the SUA farm soils. Errors in measurement methods for both soil MRC and K_s parameters and the methodologies used might be the source of inaccuracies for the obtained results. Saturated hydraulic conductivity values obtained using tension infiltrometer proved unreliable due to low K_s values for sandy soils compared to clay soils. The developed models can be applied to other soils with similar soil physical properties to the developed models. Small data points used in developing the models have been identified as the main limitation in applying the equations to other areas outside the SUA farm. The findings will expand the knowledge on hydraulic properties of SUA farm soils in addition to other existing knowledge of the soils. Also the findings will stimulate conduction of further studies on soil hydraulic properties and in developing reliable models for specific soils found in the farm. The following conclusions and recommendations are made from the study:

Conclusions

1. The PTF of Tomasella and Hodnett (1998) for SWR gave quite reasonable results at matric potentials greater than or equal to 33 kPa. This was not the case for the evaluated PTFs for predicting saturated hydraulic conductivity all of which were developed using temperate soils data.
2. The evaluated PTFs for K_s estimation are inaccurate and erratic for estimating K_s in the studied soils.
3. The developed PTFs can give good estimates of SWR and K_s compared to the evaluated PTFs for soils with similar physical properties to those found under SUA farm conditions. The slope between measured and estimated values both for soil WRC and K_s were approximately equal to one. However, the PTFs of Tomasella and Hodnet (1998) for SWR can give good estimates of soils similar to the study area at matric potentials ranging from 33 to 1500 kPa.
4. On average, estimated soil water retention and saturated hydraulic conductivity are over estimated, but the mean differences are not statistically different from zero. The mean differences may vary depending on the sample size used. The root means of squared differences are small for both soil water retention and saturated hydraulic conductivity.
5. Small sample size used in the study seems to be the main limitation in directly applying the developed equations to areas outside SUA farm soils.

Recommendations

1. Soil hydraulic properties are very important parameters in many agricultural and environmental aspects such as irrigation scheduling, drainage of agricultural and wastewater, movements of chemicals in the soils and therefore the pollution of underground waters. These parameters are in most cases not determined in routine soil survey because measurements are expensive and time consuming. There is a need of developing more PTFs for soil hydraulic properties estimation using large soil samples under different soil conditions for reliable determination of these properties.

2. It is further recommended that the models both for soil WRC and K_s estimation developed from SUA farm can be applied to soils with similar properties subject to more testing using large soil samples because sample size used in developing the models were small.

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APENDICES

Appendix 1: Soil profiles description for the fourteen studied soil profiles

Profile site and number: SFP1

Mapping unit: 24B3(UT); **Region:** Morogoro; **Map sheet No:** 183/3; **UTM Coordinates:** 37MCC 9244185; **Location:** SUA farm 200 meters west of Morogoro-Mzinga road near the Ministry of Agriculture and Food security (MAF) rodent research unity. **Elevation:** 537masl; **Parent material:** Colluvium derived from metamorphic rocks (hornblende pyroxine granulites) of the Uluguru Mountains; **Land form:** Gently sloping; **Slope:** 5.4 %; **Erosion:** None; **Deposition:** None; **Natural drainage class:** Well drained; Described by: Mdemu M.V. and Mulengera M.K., 23/10/2000

AP 0-20 cm: Brown (7.5YR 4/3) dry, (7.5YR 4/2) moist; sand clay loam; hard dry; slightly friable moist, slightly sticky and slightly plastic wet; medium angular and subangular blocky; many medium and common coarse tubular closed pores; many fine and medium roots; clear smooth boundary.

B21 20-44 cm: Dark reddish brown (2.5YR3/4) dry, (ND) moist; clay; slightly hard dry, friable moist, slightly stick and plastic wet; weak fine and medium subangular blocks; many fine and few tubular pore; common fine and few medium roots; clear smooth boundary to.

B22 44-84 cm: red (2.5YR) dry, dark reddish brown (2.5YR) moist; clay; soft dry, very friable moist, very sticky and very plastic wet; weak fine medium subangular blocky; many fine and few course roots; gradual clear boundary.

? 84-94 cm: A 10 cm thickness of rock and gravel's of granites quartz? with reddish brown nodules

B23 94-120+ cm: Dark reddish brown (2.5YR3/4) moist, reddish brown (5YR4/4) dry; clay; slightly soft dry, very friable moist, very sticky and very plastic wet; weak fine subangular blocky; many fine pore; few fine roots.

Profile site and number: SFP2

Mapping unit: 24B3(UT); **Region:** Morogoro; **Map sheet no:** 183/3; **UTM Coordinates:** 37MCC 9244444; **Location:** SUA farm 400 meters south east of Morogoro-Iringa main road; **Elevation:** 544 masl; **Parent material:** colluvium material with saprolites of mafic rocks on underlying B horizon; **Land form:** gently sloping; **Slope:** 4.6 %; **Erosion:** slightly; **Deposition:** none; **Natural drainage class:** well drained; Described by M.V.Mdemu, 24/10/2000

Ap 0-19 cm: dark brown (7.5 YR3/3) moist; sand clay, slightly hard dry, slightly friable moist, slightly sticky and slightly plastic wet; medium subangular blocky; few medium pores; many fine and few medium roots; clear smooth boundry.

AB19-54 cm: dark reddish brown (2.5YR 3/4) dry, dark reddish brown (2.5YR2.5/4) moist; clay; slightly hard to soft dry, very friable moist; slightly stick and slightly plastic wet; medium subangular blocky; few large and many fine tubular pores; common medium spherical hard nodules; few medium and many fine roots, clean smooth boundary.

Bt1 54-94 cm: dark reddish brown (5YR 3/4) dry, dark red (2.5YR 3/6) moist; clay; slightly hard dry, friable moist; very stick and very plastic wet; medium angular blocky; very few course and fine random tubular pores; many spherical hard modules; few medium and many fine roots; clear smooth boundary.

Bt2 94-132+ cm: dark brown (7.5YR 3/4) dry, dark reddish brown (5YR 3/3) moist; clay; hard dry, friable moist, very stick and very plastic wet; fine subangular blocky; very few medium fine pores; many spherical and angular nodules; very few fine roots.

Profile site and number: SFP3

Mapping unit: 14B1(RT); **Region:** Morogoro; **Map sheet no:** 183/3; **UTM Coordinates:** 37MCC 9244360; **Location:** SUA farm approx. 600 meters from Morogoro-Iringa main road; **Elevation:** 528 masl; **Parent material:** colluvium derived from metamorphic rocks; **Land form:** flat or almost flat; **Slope:** 1.2 %; **Erosion:** slight sheet erosion; **Natural drainage class:** well drained; Described by: M.V.Mdemu, 25/10/2000

Ap 0-10 cm: reddish brown (5YR 4/4) dry, dark reddish brown (5YR 3/4) moist; sand clay; slightly hard dry, friable moist, slightly sticky and slightly plastic wet; medium suangular blocky; many fine and few medium pores; few medium and common fine roots; clear smooth boundary.

A3 10-30 cm: reddish brown (5YR 4/4) dry, dark reddish brown (2.5YR 3/3) moist; clay; hard dry, very friable to friable moist, sticky and plastic wet; medium subangular blocky; common fine and few medium pores; few medium and fine roots; clear smooth boundary.

B21t 30-60 cm: red (2.5YR 4/6) dry, dark reddish brown (2.5YR 3/4) moist; clay, soft dry, friable moist, very sticky and very plastic wet; medium to fine crumbles; few fine and many very fine pores; very few fine roots; clear smooth boundary.

B22t 60-130/160+ cm: red (2.5YR 4/8) dry, red (2.5YR 4/6) moist; clay; soft dry, very friable moist, very sticky and very plastic wet; fine granules/crumbles; few fine pore; very few medium roots.

Profile site and number: SFP4

Mapping unit: 14C1(PO), **Region** Morogoro; **Map sheet no:** 183/3; **UTM Coordinates:** 37MCC 9244207; **Location:** SUA farm approx 350 meters East from Morogoro-Iringa main road; **Elevation:** 544 masl. **Parent material:** Colluvium and feldspars, which have undergone and still undergoing pedogenesis in place. **Land form:** flat to almost flat; **Erosion:** none; **Deposition:** none; **Natural drainage class:** well drained; Described by: M.V.Mdemu, 26/10/2000

Ap 0-20 cm: dark brown (7.5 YR 3/3) dry, dark brown (7.5YR 3/2) moist; sand clay loam; soft to slightly hard dry , very friable moist, non sticky and non plastic wet; medium to course angular blocky; few large and common medium discontinuous random pores; many fine and medium roots; clear smooth boundary.

AB 20-40 cm: dark reddish brown (5YR 3/3) dry, dark brown(7.5YR 3/4) moist; sandy clay loam; slightly hard dry , friable moist, non sticky and non plastic wet, coarse angular blocky; very few large and few medium tubular pores; very few medium and fine roots; clear smooth boundary.

Bcn? 40-70 cm: reddish brown (5YR 4/4) dry, dark reddish brown (5YR 3/3) moist; sand clay; hard dry, friable moist, slightly sticky and slightly plastic wet, medium angular blocky; very few medium and fine pores; few small hard spherical and angular quartzite nodules; very few fine roots; gradual boundary.

C 70-110+ cm: (ND)

Profile site and number: SFP5

Mapping unit: 24C1(ET); **Region:** Morogoro; **Map sheet no:** 183/3; **UTM Coordinates:** 37MCC 9243888; **Location:** SUA farm approx. 350 meters west of Morogoro-Mzinga road; **Elevction:** 544 masl. **Parent material:** colluvium material from mafic-metamorphic rocks; **Landform:** gently sloping; **Slope:** 3.8 %; **Erosion:** slight sheet erosion; **Deposition:** none; **Natural drainage class:** well drained, Described by M.V.Mdemu, 27/10/2000.

Ap 0-20 cm reddish brown (5YR 4/4) dry, dark reddish brown (5YR 3/3) moist; clay; slightly hard dry, friable moist, slightly sticky and slightly plastic wet; medium to large angular blocky; few medium and many fine discontinuous pores; few medium and many fine roots; clear smooth boundary.

B21 20-40 cm: dark reddish brown (2.5YR 3/4) dry, dark red (2.5YR 3/6) moist; clay; soft dry, friable moist, slightly sticky and slightly plastic wet; medium to large angular blocky; many fine pores; very few fine roots; clear smooth boundary.

B22 40-70 cm: red (5YR 4/6) red, dark red (2.5YR 3/6) moist; clay; soft to very soft dry, very friable moist, sticky and plastic wet, weak medium angular and subangular blocky; many fine pores; very few fine roots; clear smooth boundary.

B23 70-150 + cm: red (2.5YR 4/8) dry, red (2.5YR 4/6) moist; clay; very soft dry, very friable moist, very sticky and very plastic wet; weak medium angular and small subangular blocky; many fine pores.

Profile site and number: SFP6

Mapping unit: 24C1(HO); **Region:** Morogoro; **District:** Morogoro; **Map sheet no:** 183/3; **UTM Coordinates:** 37MCC 9243598; **Location:** SUA farm approx. 200 meters West of Morogoro-Iringa main road; **Elevation:** 527masl. **Parent material:** Colluvium material; **Land form:** flat or almost flat; Slope: 1.4 %;
Erosion: none; **Deposition:** slightly; **Natural drainage class:** somewhat well drained; Described by M.V.Mdemu, 28/10/2000.

Ap 0-16 cm: dark brown (7.5YR 3/4) dry, very dark brown (7.5YR 2.5/3) moist; clay; slightly hard dry, friable moist, sticky and very plastic wet; stable large to medium angular and subangular blocky; few large and many fine pores; many fine roots; clear smooth boundary.

B21t 16-40 cm: dark red (2.5 YR 3/6) dry, dark reddish brown (2.5YR 3/4) moist, clay; slightly soft dry, friable moist, sticky and very plastic wet; stable medium to larger subangular blocky; common fine random pores; few fine roots; clear smooth boundary.

B22t 40-80 cm: red (2.5YR 4/6) dry, dark reddish brown (2.5YR 3/4) moist; clay; soft dry, very friable moist, very sticky and very plastic wet; large to medium subangular blocky; few fine pores; very few fine roots; clear smooth boundary.

B23t 80-154 + cm: red (2.5YR 4/6) dry and moist; clay; slightly hard dry, friable moist, very sticky and very plastic wet; large to medium subangular blocky; non to very few fine pores, very few fine roots.

Profile site and number: SFP7

Mapping unit: 12C1(UV), **Region**: Morogoro; **Map sheet no**. 183/3; **UTM Coordinates**: 37MCC 9243652. **Location**: SUA farm approx. 1 kilometer East of Morogoro-Iringa main road; **Elevation**: 514 masl; **Parent material**: colluvium and in-situ; **Landform**: slightly depression; **Slope**: 1.3 % flat or almost flat; **Erosion**: none; **Deposition**: common; Natural drainage class: poorly drained; Described by M.V.Mdemu, 9/11/2000.

Ap 0-15 cm: very dark gray (2.5Y 3/1) dry, black (2.5Y 2.5/1) moist; few medium faint reddish brown mottles; clay; hard dry, slightly friable moist, very sticky and very plastic wet; course medium subangular blocky; very few medium and fine pores; many medium and fine roots; clear smooth boundary.

B2 15-40 cm: black (2.5Y 2.5/1) moist; common medium distinct reddish brown and grayish mottles; clay; hard dry, slightly friable moist, very sticky and very plastic wet; coarse small crumbles and course medium subangular blocky; common fine roots; diffuse boundary

B2g 40-130+cm: very dark gray (2.5Y 3/1) moist, common medium distinct reddish brown, pale grey and greyish mottles; clay; hard dry, slightly friable moist, very sticky and very plastic wet; coarse small crumbles; very few fine roots.

Profile site and number: SFP8

Mapping unit: 12C1(UV); **Region**: Morogoro; **District**: Morogoro; **Map sheet no**: 183/3; **UTM coordinates**: 37MCC 9243552. **Location**: SUA farm approx. 1.5 kilometers East of Morogoro – Iringa road; **Elevation**: 519 masl; **Parent material**: colluvium and in-situ; **Landform**: slight depression; **Slope**: 2.4 % gently sloping; **Erosion**: none; **Deposition**: common; **Natural drainage class**: poorly drained; Described by M.V.Mdemu, 01/11/2000.

Ap 0-30cm: black (5YR 2.5/1) dry; common medium distinct reddish brown mottles; sandy clay; hard dry, slightly friable moist, sticky and plastic wet, medium coarse medium to small subangular blocky; few fine pores; many medium and fine roots; clear smooth boundary

Btg 30-105 cm: brown (7.5YR 4/2) moist; common medium distinct reddish brown mottles; clay; hard dry, slightly friable moist, few medium and many fine pores; very few medium roots; clear smooth boundary.

C 105-120+ cm: (ND)

Profile site and number: SFP9

Mapping unit: 14B1 (HU); **Region**: Morogoro, **District**: Morogoro; **Map sheet no**: 183/3; **UTM coordinates**: 37MCC 9242897. **Location**: SUA farm approx. 1km east of Morogoro-Iringa main road; **Elevation**: **Parent material**: colluvium and in-situ; **Land form**: plain; **Slope**: 1 % flat or almost flat; **Erosion**: none; **Deposition**: none; **Natural drainage class**: well drained; Described by M.V.Mdemu, 30/10/2000.

Ap 1-19 cm: brown (10YR 4/3) dry, dark brown (10YR 3/3) moist; sand clay; hard dry, slightly friable to friable moist, slightly sticky and slightly plastic wet; hard large to medium angular and subangular blocky; common medium and small random pores; few medium and fine roots; clear smooth boundary.

Bs? 19-40 cm: brown (7.5YR 4/3) dry, dark brown (7,5YR 3/3) moist; clay; hard dry, slightly friable moist, very sticky and very plastic wet; large columnar and medium angular and subangular blocky; few medium and common fine pores; few fine roots; clear smooth boundary.

B21 40-62 cm: strong brown (7.5YR 4/6) dry, reddish brown (ND) moist; loamy sand; very soft dry, very friable to loose moist; non sticky and non plastic wet; small angular and subangular blocky; common fine pores; very few fine roots, clear smooth boundary.

B22 62-84 cm: strong brown (10YR 4/6) dry, dark brown (7.5YR 3/4) moist; sand clay loam; very soft dry, very friable moist, non sticky and non plastic wet; medium to small subangular blocky and medium granules; medium fine pores; clear smooth boundary.

Bwt 84-110 cm: brown (10YR 4/3) dry, dark brown (10YR 3/3) moist; clay; slightly hard dry, friable moist, very sticky and very plastic wet; hard medium angular blocky; few medium and many fine pores; very few fine roots; clear smooth boundary.

Bt 110-154+cm: strong brown (7.5 YR 4/6) dry, brown (7.5 YR 4/4) moist; clay; slightly soft dry, friable moist, very sticky and very plastic wet; medium to small angular and subangular blocky; common fine and few medium pores.

Profile site and number: SFP10

Mapping unit: 24C1(HO); **Region**: Morogoro; **District**: Morogoro; **Map sheet no**: 183/3; **UTM Coordinates**: 37MCC 9242411. **Location**: SUA farm 200 meters South west of Morogoro-Mzinga road; **Elevetion**: 559 masl; **Parent material**: colluvium and in-situ; **Landform**: plain; **Slope**: 3.2 % gently sloping; **Erosion**: slight sheet erosion; **Deposition**: none; **Natural drainage class**: well drained; Described by M.K Mulengera and M.V.Mdemu; 29/10/2000.

Ap 0-18 cm: brown (10Y 4/3) dry, dark brown (10YR 3/3) moist; sand clay; slightly soft dry, friable moist, moderate sticky and moderately plastic wet; fine crumbles and medium angular and subangular blocky; few medium pores; few medium and many fine roots; clear smooth boundary.

B2t1 18-110 cm: strong brown (7.5YR 5/6) dry, yellowish red (5YR 5/8) moist; clay; soft dry, very friable moist, slightly sticky and slightly plastic wet, medium angular and subangular blocky; very few medium and many fine pores; very few fine roots; clear smooth boundary.

B2t2 110-140+ cm: strong brown (7.5YR 5/6) dry, strong brown (7.5YR 4/6) dry; clay; slightly soft dry, friable moist, very sticky and very plastic wet; medium fine angular blocky; common fine pores

Profile site and number: SFP11

Mapping unit: 14C1(P); **Region**: Morogoro; **District**: Morogoro; **Map sheet no**: 183/3; **UTM Coordinates**: 37MCC 9244177. **Location**: SUA farm approx. 300 meters South east of Morogoro-Iringa main road; **Elevation**: 552masl; **Parent material**: colluvium and in-situ pedogenesis; **Land form**: Plain; **Slope**: 1.6 %; flat or almost flat; **Erosion**: none; **Deposition**: none; **Natural drainage class**: well drained; Described by M.V.Mdemu, 31/10/2000

Ap 0-10 cm; brown (7.5YR 4/3) dry, dark brown (7.5YR 3/3) moist; clay; slightly hard dry, friable moist; very sticky and very plastic wet; medium angular to subangular blocky; few large and many fine pores; few large and many fine roots; clear smooth boundary.

B21t 10-34 cm: reddish brown (5YR 4/4) dry, dark reddish brown (5YR 3/4) moist; clay; soft dry, very friable moist; sticky and plastic wet; medium angular and small subangular blocky; common fine pores; very few medium and common fine roots; clear smooth boundary.

B22t 34-70cm: red (2.5YR4/6) dry, reddish brown (2.5YR4/4) moist; clay; very soft dry, very friable moist, sticky and plastic wet; fine large to small angular and subangular blocky; few fine pores; very few fine roots; clear smooth boundary to.

B23t 70-120 cm: red (2.5 YR 4/6) dry, reddish brown (2.5YR 4/4) moist; clay; very soft dry, very friable moist, slightly sticky and sticky and slightly plastic to plastic; medium crumbles and fine subangular blocky; common fine pores; clear smooth boundary.

B24t 120-153+ cm: yellowish red (5YR 4/6) dry and moist; clay; slightly soft dry, friable moist, slightly sticky and slightly to moderately plastic wet; medium crumbles and fine small subangular blocky; common fine pores.

Profile site and number: SFP12

Mapping unit: (36A1); **Region**: Morogoro; **District**: Morogoro; **Map sheet no**: 183/3; **UTM coordinates**: 9244914; **Location**: SUA farm approx. 1km west of Morogoro-Iringa main road. **Elevation**: 518 masl
Parent material: colluvium material of granite rocks from Mindu mountains; **Land form**: undulating; **Slope**: 2.5 % gently sloping; **Erosion**: slight; **Deposition**: none; **Natural drainage class**: somewhat excessively drained; Described by M.V. Mdemu and M.K. Mulengera, 7/11/2000.

Ap 0-35 cm: dark gray (10YR 4/1) dry, very dark gray (10YR 3/1) moist; loamy sand; slightly hard dry, very friable to loose moist; non to slightly sticky and non plastic wet; fine angular and subangular blocky; small medium and many fine pores, small medium and many fine roots, clear smooth boundary.

B21 35-110 cm: dark grayish brown (10YR 4/2) dry, very dark grayish brown (10YR 3/2) moist; loamy sand; slightly hard dry, very friable to loose moist; non sticky and non to slightly sticky wet; fine angular blocky; common fine pores; few medium and fine roots; clear smooth boundary.

B22 110-140+ cm: dark grayish brown (10YR 4/2) dry, very dark grayish brown (10YR3/2) moist; loamy sand; very hard dry, friable moist; non sticky and non to slightly plastic wet; large to small course subangular blocky; common fine pore; very few fine roots.

Profile site and number: SFP13

Mapping unit: (24A1); **Region**: Morogoro; **District**: Morogoro; **Map sheet no**: 183/3; **UTM Coordinates**: 37MCC 9245271. **Location**: SUA farm approximately 1kilometer west of Morogoro-Iringa main road; **Elevation**: 520 masl; **Parent material**: colluvium material of granite rocks of the Mindu mountain; **Land form**: Plain; **Slope**: 3.2 % gently slopping; **Erosion**: none; **Deposition**: slightly; **Natural drainage class**: well drained; Described by M.V.Mdemu, 8/11/2000.

Ap 0-36 cm: grayish brown (2.5Y 5/2) dry, very dark gray (2.5Y 3/1) moist; sandy loam; hard dry, friable moist, non sticky to slightly sticky and non plastic wet; smooth large to small angular blocky; few medium and many fine pores; many fine roots; clear smooth boundary.

BA 36-66 cm: dark grayish brown (2.5YR 4/2) dry, very dark grayish brown (10YR 3/2) moist; loamy sand; slightly hard dry, very friable to loose moist, non to slightly sticky and slightly plastic wet; large to medium fine subangular blocky; common fine pores, very few fine roots, clear smooth boundary.

B 66-110 cm: brown (10YR 4/3) dry, dark grayish brown (10YR 4/2) moist; loamy sand; slightly soft dry, very friable to loose moist, non sticky and non plastic wet; medium to small angular blocky; few fine pores.

C 110-140+ cm: pale brown (10YR 5/3) dry, brown (10YR 4/3) moist, loamy sand; soft dry, loose moist, non sticky and non plastic wet, medium to small angular blocky; very few pores;

Profile site and number: SFP14

Mapping unit. (23A1); **Region**: Morogoro; **District**: Morogoro; **Map sheet no**: 183/3; **UTM coordinates**: 9245019; **Location**: SUA farm approximately 1.5 kilometers west of Morogoro-Iringa main road. **Elevation**: 522masl; **Parent material**: colluvium material from granites; **Landform**: plain; **Slope**: 2.6 %, gently slopping; **Erosion**: none; **Deposition**: common; **Natural drainage class**: excessively drained; Described by M.V.Mdemu, 8/11/2000.

Ah 0-25 cm; dark gray (2.5Y4/1) dry, black (2.5Y 2.5/1) moist; sand; very soft dry, loose moist, non sticky and non plastic wet; small smooth crumbles and fine subangular blocky; small medium and many fine pores; small medium and many fine roots; clear weavy boundary.

Ab 25-55 cm: dark gray (2.5Y 4/1) dry, very dark gray (2.5Y 3/1) moist; sand; very soft dry, loose moist; non sticky and non plastic wet; fine small angular and subangular blocky; common fine pores; many medium and fine roots; clear smooth boundary.

B21 55-94 cm: grayish brown (2.5Y 5/2) dry, very dark grayish brown (2.5Y 3/2) moist; sand; very soft dry, loose moist, non sticky and non plastic wet; coarse granules and small sub angular blocky; common fine pore; many fine and few medium roots; clear smooth boundary.

B22 94 –150 cm: dark grayish brown (10YR 4/2) dry, very dark grayish brown (10YR 3/2) moist; sand; very soft dry, loose moist; non sticky and non plastic wet; medium subangular blocky and coarse granules; very few fine pores; very few medium roots.

Appendix 2: Measured soil physical properties

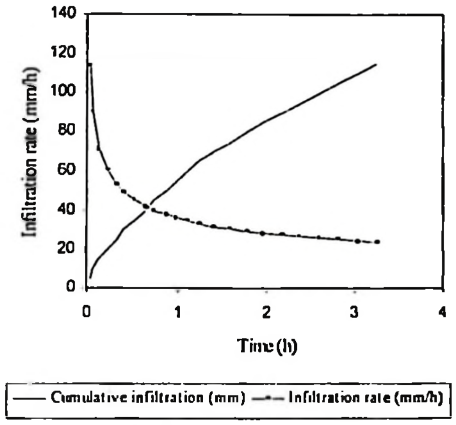
Table 2.1A: Basic soil physical properties used in the study

PF	Horizon	Munsell color notation		Particle size distribution			%OC	BD	porosity	texture
		dry	moist	%clay	%silt	%sand		(g/cm^3)	(%)	
1	Ap 0-20	7.5YR4/3	7.5YR4/2	28	9	63	1.29	1.49	44	SCL
	B21 20-44	2.5YR3/4	N.D	52	6	42	0.67	1.23	54	C
	B22 44-84	2.5YR	2.5YR	54	6	40	0.43	1.38	48	C
	B23 94-120	5YR4/4	2.5YR3/4	52	6	42	0.28	1.49	44	C
2	Ap 0-19	7.5YR3/4	7.5YR3/3	47	5	48	1.10	1.21	54	SC
	AB 19-54	2.5YR3/4	2.5YR2.5/4	70	6	24	0.74	1.18	55	C
	Bt1 54-94	5YR3/4	2.5YR3/6	65	7	28	0.51	1.26	53	C
	Bt2 94-132	7.5YR3/4	5YR3/3	64	8	28	0.35	1.31	51	C
3	Ap 0-10	5YR4/4	5YR3/4	45	6	49	0.90	1.42	46	SC
	A3 10-30	5YR4/4	5YR3/3	53	4	43	0.67	1.29	51	C
	B21t 30-60	2.5YR4/6	2.5YR3/4	59	6	35	0.51	1.21	54	C
	B22t 60-130	2.5YR4/8	2.5YR4/6	52	8	40	0.20	1.15	57	C
4	Ap 0-20	7.5YR3/3	7.5YR3/2	31	4	65	0.82	1.40	47	SCL
	AB 20-40	5YR3/3	7.5YR3/4	31	6	63	0.47	1.46	45	SCL
	Bcn? 40-70	5YR4/4	5YR3/3	37	6	57	0.47	1.59	40	SC
5	Ap 0-20	5YR4/4	5YR3/3	53	8	39	0.90	1.21	54	C
	B21 20-40	2.5YR3/4	2.5YR3/6	54	11	35	0.67	1.13	57	C
	B22 40-70	5YR4/6	2.5YR3/6	64	6	30	1.25	1.19	55	C
	B23 70-150	2.5YR4/8	2.5YR4/6	61	11	28	0.35	1.11	58	C
6	Ap 0-16	7.5YR3/4	7.5YR2.5/3	64	8	28	1.49	1.20	55	C
	B21t 16-40	2.5YR3/6	2.5YR3/4	73	6	21	0.86	1.19	55	C
	B22t 40-90	2.5YR4/6	2.5YR3/4	77	4	19	0.47	1.20	55	C
	B23t 90-154	2.5YR4/6	2.5YR4/6	76	8	16	0.59	1.20	55	C
7	Ap 0-15	2.5Y3/1	2.5Y2.5/1	61	15	24	2.58	1.18	55	C
	B2 15-40	N.D	2.5Y2.5/1	71	4	25	2.27	1.23	53	C
	B2g 40-130	N.D	2.5Y3/1	68	4	28	1.86	1.45	45	C
8	Ap 0-30	5YR2.5/1	N.D	46	6	48	1.76	1.27	52	SC
	Btg 30-105	N.D	7.5YR4/2	54	8	28	0.90	1.45	45	C
9	Ap 0-19	10YR4/3	10YR3/3	26	6	68	1.17	1.39	48	SCL
	Bs? 19-40	7.5YR4/3	7.5YR3/3	51	11	38	0.82	1.58	40	C
	B21 40-62	7.5YR4/6	N.D	9	4	87	0.24	1.58	40	LS
	B22 62-84	7.5YR4/6	7.5YR3/4	21	3	76	0.12	1.29	51	SCL
	Bwt 84-110	10YR4/3	10YR3/3	65	1	34	0.32	1.34	49	C
10	Ap 0-18	10YR4/3	10YR3/3	46	6	48	1.02	1.21	54	SC
	B2t1 18-110	7.5YR5/6	5YR5/8	63	3	34	0.32	1.02	61	C
	B2t2 110-140	7.5YR5/6	7.5YR4/6	63	3	34	0.16	1.19	55	C
11	Ap 0-10	7.5YR4/6	7.5YR3/3	47	8	45	1.45	1.23	54	C
	B21t 10-34	5YR4/4	5YR3/4	63	3	34	0.74	1.16	56	C
	B22t 34-70	2.5YR4/6	2.5YR4/4	67	6	27	0.47	1.21	54	C
	B23t 70-120	2.5YR4/6	2.5YR4/4	70	3	27	0.32	1.14	57	C
	B24t 120-153	5YR4/6	5YR4/6	71	6	23	0.28	1.16	56	C
12	Ap 0-35	10YR4/1	10YR3/1	9	9	82	0.35	1.38	48	LS
	B21 35-110	10YR4/2	10YR3/2	12	4	84	0.12	1.53	42	LS
	B22 110-140	10YR4/2	10YR3/2	11	5	84	0.08	1.59	40	LS
13	Ap 0-36	2.5Y5/2	2.5Y3/1	12	9	79	0.78	1.44	46	SL
	BA 36-66	2.5YR4/2	10YR3/2	9	7	84	0.55	1.52	43	LS
	B 66-120	10YR4/3	10YR4/2	9	7	84	0.16	1.47	45	LS
14	Ah 0-25	2.5Y4/1	2.5Y2.5/1	4	7	89	0.59	1.26	53	S
	Ab 25-55	2.5Y4/1	2.5Y3/1	5	2	93	0.24	1.39	47	S
	B21 55-94	2.5Y5/2	2.5Y3/2	2	2	96	0.12	1.56	41	S
	B22 94-150	10YR4/2	10YR3/2	2	2	96	0.08	1.59	40	S

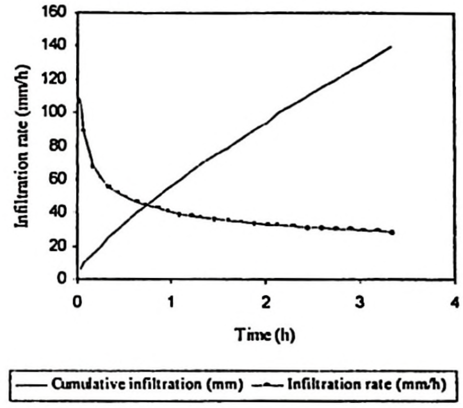
Table 2.2A: Measured soil water retention (% cm^3cm^{-3}) at determined matric potentials

PF No.	Horizon	0.1kPa	1kPa	10kPa	20kPa	33kPa	50kPa	100kPa	1500kPa	AWC
1	Ap 0-20	39.572	33.829	30.020	27.587	26.986	25.531	21.894	15.295	11.695
	B21 20-44	36.853	32.953	30.957	28.971	27.566	26.519	23.900	22.070	5.500
	B22 44-84	45.122	36.568	33.758	31.721	30.285	29.575	27.800	25.689	4.601
	B23 94-120	38.147	34.409	32.953	31.874	30.346	29.523	27.464	26.748	3.602
2	Ap 0-19	43.941	33.320	30.703	29.012	26.629	25.562	22.892	19.570	7.060
	AB 19-54	38.065	31.415	28.452	27.332	26.711	26.010	24.257	20.187	6.523
	Bt1 54-94	41.120	35.845	33.686	31.874	30.489	30.140	29.267	24.080	6.410
	Bt2 94-132	35.784	33.432	32.556	31.670	31.293	30.546	28.676	25.466	5.824
3	Ap 0-10	38.727	31.314	27.607	24.470	23.534	22.364	19.440	19.295	4.235
	A3 10-30	36.181	28.574	26.232	23.992	22.984	21.881	19.124	18.169	4.811
	B21t 30-60	40.377	29.216	25.234	22.719	21.334	20.630	18.870	17.597	3.733
	B22t 60-130	47.026	36.660	32.077	27.933	25.468	24.910	23.513	20.869	4.601
4	Ap 0-20	41.929	32.822	29.482	26.619	25.726	25.192	23.858	15.042	10.688
	AB 20-40	39.168	31.726	28.640	26.325	25.157	24.026	21.198	16.064	9.096
	Bcn? 40-70	38.599	34.102	31.807	29.756	28.934	28.191	26.335	20.641	8.289
5	Ap 0-20	39.603	30.896	28.941	27.923	26.670	26.109	24.705	22.426	4.244
	B21 20-40	41.100	34.460	31.466	28.931	27.587	26.455	23.625	21.737	5.853
	B22 40-70	45.173	37.047	31.741	28.187	26.864	26.442	25.387	24.716	2.144
	B23 70-150	47.444	36.609	32.811	29.847	29.002	27.736	24.572	24.387	4.613
6	Ap 0-16	44.969	36.615	34.383	31.831	30.298	29.904	28.920	26.650	3.650
	B21t 16-40	44.465	36.759	34.475	32.644	31.626	31.070	29.681	29.383	2.248
	B22t 40-90	44.548	38.264	35.726	32.711	31.431	30.938	29.706	29.278	2.153
	B23t 90-154	ND	ND	ND	ND	ND	ND	ND	ND	ND
7	Ap 0-15	52.363	46.334	43.707	42.363	41.069	40.138	37.811	25.882	15.188
	B2 15-40	51.884	47.841	45.591	44.603	43.238	42.112	39.297	29.760	13.480
	B2g 40-130	53.167	47.933	45.998	42.933	41.365	40.300	37.637	31.547	7.824
8	Ap 0-30	48.523	45.937	45.143	44.012	43.605	42.182	38.625	20.305	23.295
	Btg 30-105	41.018	38.686	37.597	36.660	35.193	34.559	32.974	27.296	7.894
9	Ap 0-19	37.149	28.625	25.631	23.727	22.648	21.897	20.020	12.907	9.743
	Bs? 19-40	42.658	37.821	36.222	35.020	34.246	33.510	31.670	28.721	5.529
	B21 40-62	37.821	25.143	23.065	21.721	21.222	20.579	18.971	5.407	15.813
	B22 62-84	39.226	28.218	27.128	25.947	23.656	22.754	20.499	9.426	14.234
	Bwt 84-110	47.251	42.271	39.470	36.792	35.509	34.887	33.330	29.231	6.279
10	Ap 0-18	39.236	29.287	26.365	24.124	22.862	22.262	20.764	19.399	3.461
	B2t1 18-110	45.855	38.259	34.552	31.079	28.208	27.687	26.385	21.852	6.358
	B2t2 110-140	47.107	42.142	39.350	36.680	35.401	34.780	33.228	25.482	9.918
11	Ap 0-10	39.216	30.682	28.289	26.670	25.204	24.878	24.063	20.277	4.923
	B21t 10-34	43.880	32.902	29.684	27.240	25.794	24.744	22.118	21.217	4.573
	B22t 34-70	48.768	34.603	30.428	26.914	25.703	25.447	24.807	21.839	3.861
	B23t 70-120	40.244	30.957	26.904	26.385	23.697	23.022	21.334	20.485	3.215
	B24t 120-153	44.929	36.965	33.411	30.489	28.697	27.716	25.265	24.546	4.154
12	Ap 0-35	36.548	18.569	16.416	13.543	12.345	11.875	10.701	5.453	6.897
	B21 35-110	34.112	18.071	15.350	13.462	12.792	12.386	11.371	6.754	6.036
	B22 110-140	33.198	19.582	17.587	15.947	14.369	13.374	10.886	6.668	7.702
13	Ap 0-36	36.152	21.909	19.350	16.822	15.411	14.703	12.934	7.119	8.291
	BA 36-66	35.401	19.012	15.916	13.632	12.737	12.090	10.473	5.663	7.077
	B 66-120	36.811	18.323	16.049	14.506	13.693	12.932	11.029	5.489	8.201
14	Ah 0-25	48.183	22.152	16.711	14.365	13.381	12.969	11.939	2.594	10.786
	Ab 25-55	36.701	16.030	14.213	13.299	12.670	11.832	9.736	2.617	10.053
	B21 55-94	36.995	10.914	8.325	7.391	6.843	6.335	5.066	1.367	5.473
	B22 94-150	40.021	12.233	10.741	10.226	9.650	8.795	6.656	1.396	8.254

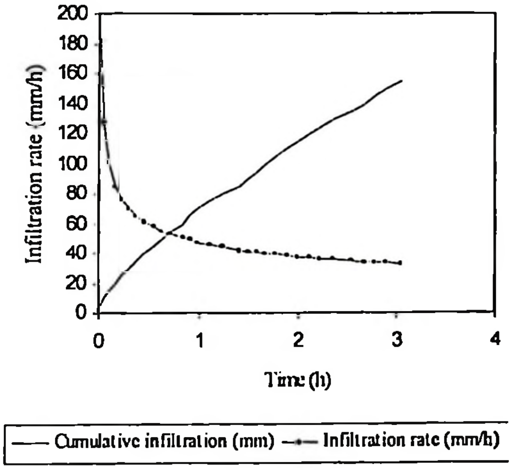
Appendix 3: Typical infiltration characteristic curves for the soils found on SUA farm



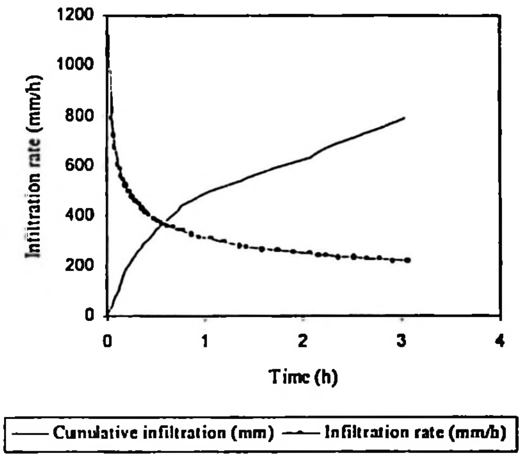
SFP 7-Clay (C)



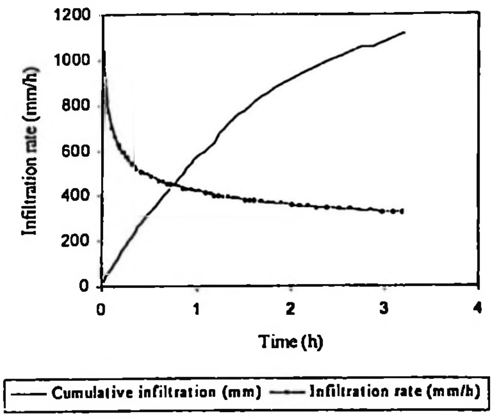
SFP 8-Sandy clay (SC)



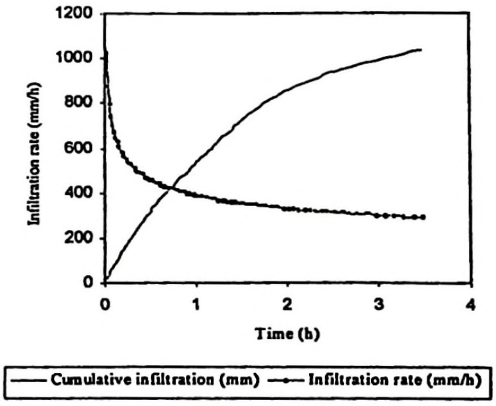
SFP 9-Sandy Clay Loam (SCL)



SFP 12-Loamy Sand (LS)



SFP 13-Sandy Loam (SL)



SFP 14-Sandy (S)

Appendix 4: Measured and estimated soil moisture retention (% cm^{3}cm^{-3}) by Tomasella and Hodnett (1998) PTFs at determined matric potentials

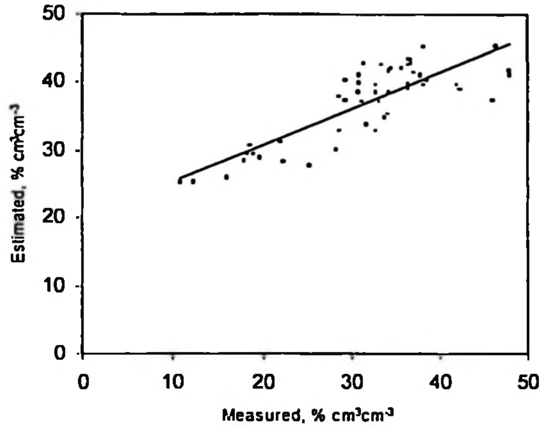
PF No.	Horizon & depth (cm)	1 kPa Measured	1 kPa Estimated	10 kPa Measured	10 kPa Estimated	33 kPa Measured	33 kPa Estimated	100 kPa Measured	100 kPa Estimated	1500 kPa Measured	1500 kPa Estimated	AWC Measured	AWC Estimated
1	Ap 0-20	33.829	34.91	30.020	23.68	26.986	19.19	21.894	16.35	15.295	13.35	11.695	5.84
	B21 20-44	32.953	38.72	30.957	29.76	27.566	27.61	23.900	23.66	22.070	22.40	5.500	5.21
	B22 44-84	36.568	39.17	33.758	30.40	30.285	28.42	27.800	24.37	25.689	23.19	4.601	5.22
	B23 94-120	34.409	38.72	32.953	29.76	30.346	27.61	27.464	23.66	26.748	22.40	3.602	5.21
2	Ap 0-19	33.320	37.06	30.703	27.61	26.629	25.16	22.892	21.54	19.570	20.27	7.060	4.89
	AB 19-54	31.415	42.77	28.452	35.53	26.711	34.88	24.257	29.98	20.187	29.53	6.523	5.35
	Bt1 54-94	35.845	42.17	33.686	34.47	30.489	33.29	29.267	28.60	24.080	27.70	6.410	5.59
	Bt2 94-132	33.432	42.48	32.556	34.69	31.293	33.31	28.676	28.61	25.466	27.45	5.824	5.86
3	Ap 0-10	31.314	37.14	27.607	27.51	23.534	24.78	19.440	21.21	19.295	19.63	4.235	5.15
	A3 10-30	28.574	37.88	26.232	28.99	22.984	27.16	19.124	23.28	18.169	22.50	4.811	4.66
	B21t 30-60	29.216	40.29	25.234	32.00	21.334	30.44	18.870	26.12	17.597	25.17	3.733	5.26
	B22t 60-130	36.660	39.78	32.077	30.84	25.468	28.46	23.513	24.40	20.869	22.70	4.601	5.76
4	Ap 0-20	32.822	32.93	29.482	21.93	25.726	18.27	23.858	15.56	15.042	13.79	10.688	4.49
	AB 20-40	31.726	33.99	28.640	23.02	25.157	19.13	21.198	16.29	16.064	14.09	9.096	5.04
	Bcn? 40-70	34.102	35.34	31.807	24.94	28.934	21.55	26.335	18.40	20.641	16.46	8.289	5.09
5	Ap 0-20	30.896	40.00	28.941	31.16	26.670	28.87	24.705	24.75	22.426	23.10	4.244	5.77
	B21 20-40	34.460	41.82	31.466	33.11	27.587	30.55	23.625	26.21	21.737	23.94	5.853	6.60
	B22 40-70	37.047	41.42	31.741	33.61	26.864	32.46	25.387	27.88	24.716	27.15	2.144	5.30
	B23 70-150	36.609	43.39	32.811	35.36	29.002	33.38	24.572	28.67	24.387	26.72	4.613	6.66
6	Ap 0-16	36.615	42.48	34.383	34.69	30.298	33.31	28.920	28.61	26.650	27.45	3.650	5.86
	B21t 16-40	36.759	43.44	34.475	36.50	31.626	36.09	29.681	31.04	29.383	30.72	2.248	5.38
	B22t 40-90	38.264	45.18	35.726	38.55	31.431	38.16	29.706	32.83	29.278	32.21	2.153	5.95
	B23t 90-154	ND	N.D	ND	N.D	ND	N.D	ND	N.D	ND	N.D	ND	N.D
7	Ap 0-15	46.334	45.51	43.707	37.53	41.069	35.08	37.811	30.14	25.882	27.32	15.188	7.76
	B2 15-40	47.841	41.93	45.591	34.77	43.238	34.43	39.297	29.60	29.760	29.63	13.480	4.81
	B2g 40-130	47.933	41.26	45.998	33.81	41.365	33.22	37.637	28.54	31.547	28.44	7.824	4.78
8	Ap 0-30	45.937	37.37	45.143	27.83	43.605	25.19	38.625	21.56	20.305	20.03	23.295	5.16
	Btg 30-105	38.686	40.23	37.597	31.48	35.193	29.27	32.974	25.10	27.296	23.49	7.894	5.78
9	Ap 0-19	28.625	32.87	25.631	21.41	22.648	17.11	20.020	14.54	12.907	12.11	9.743	5.00
	Bs? 19-40	37.821	41.14	36.222	32.15	34.246	29.34	31.670	25.16	28.721	22.76	5.529	6.58
	B21 40-62	25.143	27.98	23.065	14.87	21.222	9.39	18.971	7.83	5.407	5.07	15.813	4.31
	B22 62-84	28.218	30.15	27.128	18.18	23.656	13.81	20.499	11.68	9.426	9.68	14.234	4.13
	Bwt 84-110	42.271	38.99	39.470	31.21	35.509	30.73	33.330	26.38	29.231	26.80	6.279	3.93

10	Ap 0-18	29.287	37.37	26.365	27.83	22.862	25.19	20.764	21.56	19.399	20.03	3.461	5.16
	B2t1 18-110	38.259	39.60	34.552	31.66	28.208	30.78	26.385	26.42	21.852	26.31	6.358	4.47
	B2t2 110-140	42.142	39.60	39.350	31.66	35.401	30.78	33.228	26.42	25.482	26.31	9.918	4.47
11	Ap 0-10	30.682	38.65	28.289	29.24	25.204	26.44	24.063	22.65	20.277	20.72	4.923	5.72
	B21t 10-34	32.902	39.60	29.684	31.66	25.794	30.78	22.118	26.42	21.217	26.31	4.573	4.47
	B22t 34-70	34.603	42.09	30.428	34.57	25.703	33.67	24.807	28.93	21.839	28.34	3.861	5.33
	B23t 70-120	30.957	41.18	26.904	33.91	23.697	33.60	21.334	28.88	20.485	29.08	3.215	4.52
	B24t 120-153	36.965	42.99	33.411	35.86	28.697	35.29	25.265	30.33	24.546	29.93	4.154	5.36
12	Ap 0-35	18.569	30.63	16.416	17.58	12.345	11.52	10.701	9.68	5.453	5.82	6.897	5.69
	B21 35-110	18.071	28.66	15.350	15.83	12.792	10.60	11.371	8.89	6.754	6.26	6.036	4.34
	B22 110-140	19.582	28.96	17.587	16.05	14.369	10.62	10.886	8.90	6.668	6.02	7.702	4.60
13	Ap 0-36	21.909	31.31	19.350	18.55	15.411	12.73	12.934	10.73	7.119	7.01	8.291	5.72
	BA 36-66	19.012	29.57	15.916	16.50	12.737	10.66	10.473	8.94	5.663	5.52	7.077	5.14
	B 66-120	18.323	29.57	16.049	16.50	13.693	10.66	11.029	8.94	5.489	5.52	8.201	5.14
14	Ah 0-25	22.152	28.45	16.711	14.89	13.381	8.64	11.939	7.19	2.594	3.54	10.786	5.10
	Ab 25-55	16.030	26.02	14.213	12.50	12.670	6.92	9.736	5.69	2.617	3.19	10.053	3.73
	B21 55-94	10.914	25.35	8.325	11.53	6.843	5.71	5.066	4.64	1.367	2.00	5.473	3.70
	B22 94-150	12.233	25.35	10.741	11.53	9.650	5.71	6.656	4.64	1.396	2.00	8.254	3.70

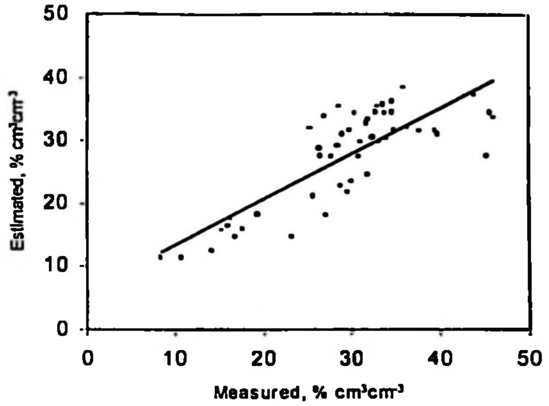
Appendix 5: Measured and predicted soil moisture retention (% cm^3cm^{-3}) by the developed PTFs at determined matric potentials

PF No.	Horizon & depth (cm)	0.1 kPa		1 kPa		10 kPa		20 kPa		33 kPa		50 kPa		100 kPa		1500 kPa		AWC	
		Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.	Meas.	Pred.
1	Ap 0-20	39.572	41.88	33.829	26.643	30.020	28.83	27.587	27.235	26.986	26.4	25.531	25.513	21.894	23.295	15.295	16.068	11.695	10.811
	B21 20-44	36.853	42.258	32.953	34.111	30.957	30.181	28.971	27.944	27.566	26.517	26.519	25.782	23.900	23.945	22.070	20.067	5.500	6.382
	B22 44-84	45.122	41.708	36.568	34.733	33.758	31.353	31.721	29.326	30.285	28.12	29.575	27.378	27.800	25.525	25.689	23.009	4.601	5.338
	B23 94-120	38.147	41.053	34.409	34.111	32.953	31.245	31.874	29.386	30.346	28.352	29.523	27.603	27.464	25.731	26.748	23.78	3.602	4.983
2	Ap 0-19	43.941	43.109	33.320	32.555	30.703	30.574	29.012	28.402	26.629	27.015	25.562	26.225	22.892	24.251	19.570	17.951	7.060	8.385
	AB 19-54	38.065	44.196	31.415	39.712	28.452	35.672	27.332	33.316	26.711	31.778	26.010	31.041	24.257	29.199	20.187	26.711	6.523	4.981
	Bt1 54-94	41.120	43.007	35.845	38.157	33.686	33.842	31.874	31.593	30.489	30.169	30.140	29.445	29.267	27.636	24.080	25.954	6.410	4.615
	Bt2 94-132	35.784	42.416	33.432	37.845	32.556	33.29	31.670	31.099	31.293	29.739	30.546	29.026	28.676	27.241	25.466	26.436	5.824	4.132
3	Ap 0-10	38.727	42.3	31.314	31.933	27.607	31.392	24.470	29.552	23.534	28.504	22.364	27.687	19.440	25.644	19.295	20.558	4.235	7.85
	A3 10-30	36.181	42.354	28.574	34.422	26.232	31.209	23.992	29.075	22.984	27.75	21.881	26.999	19.124	25.121	18.169	20.879	4.811	6.291
	B21t 30-60	40.377	42.433	29.216	36.289	25.234	31.343	22.719	29.021	21.334	27.522	20.630	26.814	18.870	25.042	17.597	22.409	3.733	5.166
	B22t 60-130	47.026	40.805	36.660	34.111	32.077	26.807	27.933	24.337	25.468	22.699	24.910	22.053	23.513	20.439	20.869	18.756	4.601	4.696
4	Ap 0-20	41.929	40.714	32.822	27.576	29.482	26.292	26.619	24.438	25.726	23.369	25.192	22.573	23.858	20.582	15.042	13.842	10.688	8.849
	AB 20-40	39.168	39.632	31.726	27.576	28.640	25.195	26.325	23.376	25.157	22.358	24.026	21.596	21.198	19.691	16.064	14.941	9.096	7.593

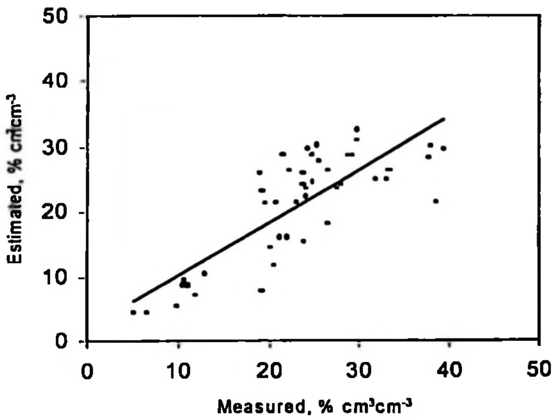
Appendix 6: Scatter plots for the measured volumetric water content versus those estimated using Tomasella and Hodnett (1998) PTFs.



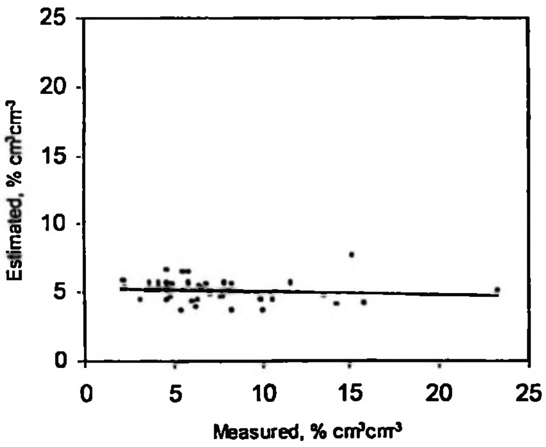
Measured volumetric soil water content versus those estimated using Tomasella and Hodnett (1998) PTFs at 1 kPa matric potential



Measured volumetric soil water content versus those estimated using Tomasella and Hodnett (1998) PTFs at 10 kPa matric potential

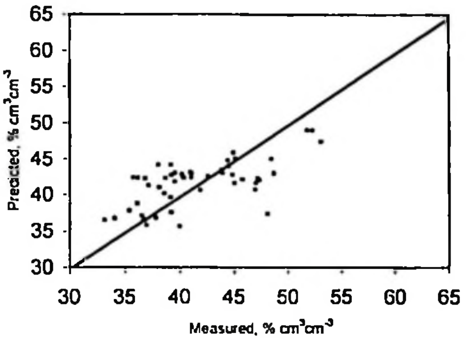


Measured volumetric soil water content versus those estimated using Tomasella and Hodnett (1998) PTFs at 100 kPa matric potential

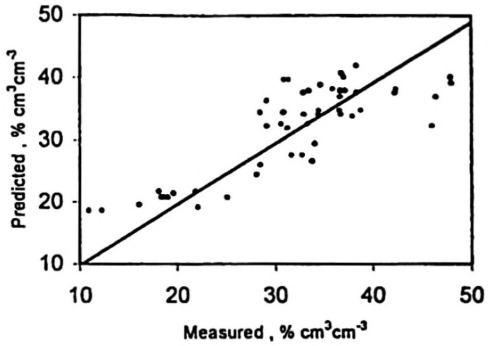


Measured volumetric soil water content versus those estimated using Tomasella and Hodnett (1998) PTFs at AWC

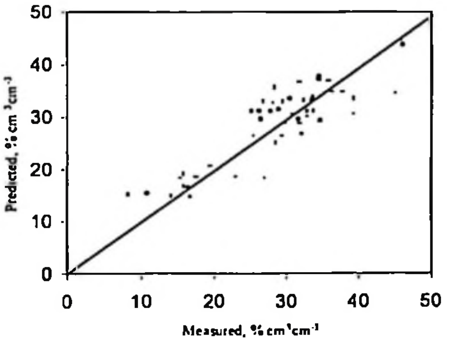
Appendix 7: Scatter plots for the measured volumetric water content versus those predicted by the developed equations at determined matric potentials



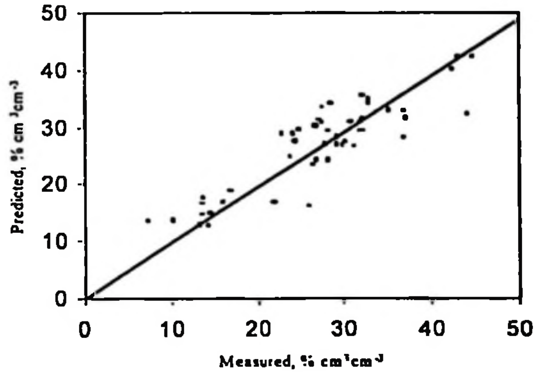
Measured volumetric soil water content at 0.1 kPa versus those predicted using Eq. 1 in Table 4.10



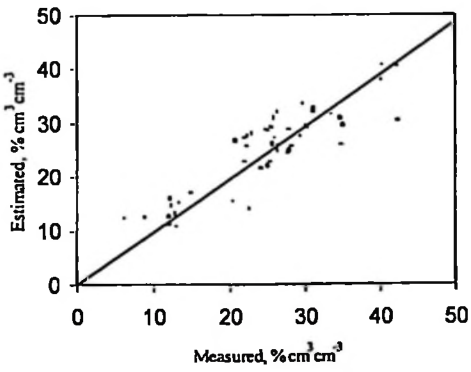
Measured volumetric soil water content at 1 kPa versus those predicted using Eq. 2 in Table 4.10



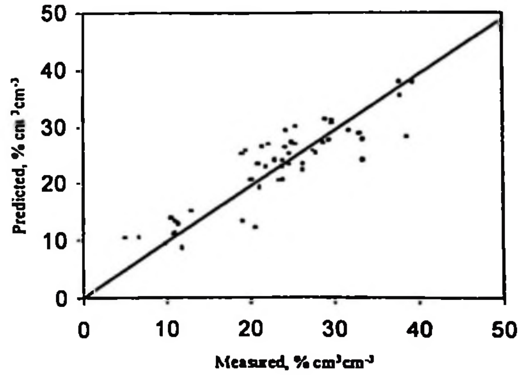
Measured volumetric soil water content at 10 kPa versus those predicted using Eq. 3 in Table 4.10



Measured volumetric soil water content at 20 kPa versus those predicted using Eq. 4 in Table 4.10



Measured volumetric soil water content at 50 kPa versus those predicted using Eq. 6 in Table 4.10



Measured volumetric soil water content at 100 kPa versus those predicted using Eq. 7 in Table 4.10