A STUDY OF THE DRAINAGE PROBLEMS IN SOME PART OF THE MWEA IRRIGATION SCHEME, KENYA

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DECLARATION

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

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This thesis has been submitted for examination with my approval as University supervisor.

30/11/8

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ABSTRACT

The red soils occupy some parts of Mwea Irrigation Scheme. In particular, the Tebere Section of the Scheme has these soils occurring at higher elevations than the black cotton soils which occur in the depressions. The black soils are irrigated under rice cultivation. The red soils in Tebere are irrigated to a limited extent. The irrigated plots are grown with vegetable and fruit trees.

The red soils (kaolinitic clay loams) have extremely high infiltration rates. The result of their irrigation is that water percolates into deeper layers, consequently finding its way by seepage to lower lying black soils.

The main canals which supply irrigation water to Tebere Section also run over the red soils. For all their lengths the canals (left and right branches) are not lined and therefore water losses from them is a possible source on the drainage problems. However, the total surface area of the canal is far less than that of the basin and furrow-irrigated plot on which water use efficiency has been studied.

Although the present study reveals that canal losses and deep percolation losses contribute substantially to the poor drainage of the black soils, rainfall has also been identified as an important component.

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CHAPTER 1

1. INTRODUCTION

The greatest limiting factor in irrigated agriculture in Kenya today is water resources. Careful distribution of controlled quantities of water to suitable areas of land, together with large number of essential complementary inputs, however, will allow increased crop production. This will mean more food for the ever increasing Kenyan population who can no longer depend entirely on rainfed agriculture.

It is a recognised fact that information on irrigated agriculture in Kenya is not enough. Adequate information wooud therefore enable government planners, senior officials and administrators to establish firm objectives for irrigation projects, implement irrigation plans, direct irrigation activities and operate and manage irrigation schemes properly.

One area where information on irrigation is greatly needed is the Mwea Irrigation Settlement Scheme in Kirinyaga District of the Central Province of Kenya. In this scheme a number of operational problems exist. Most of these problems relate to soil and water management.

The soils in the scheme consist of free draining reddish brown lateritic clay loams (Humic Nitosols) and impervious heavy (black cotton) clays (Vertisols). The lateritic clay loams are commonly referred to as the red soils of Mwea. These red soils are generally rather shallow and are underlain by murram (ferricrete) and volcanic tuff.

There are five sections of the Mwea Scheme. These are Tebere, Mwea, Thiba, Karaba and Wamumu. The total acreage of the scheme is 11,900 hectares and of this area the'black cotton' soils comprise 7,150 hectares while the 'red soils' together with the transitional soil from the red to black comprise 4,750 hectares. The red soil patches are used for growing crops under rainfed agriculture.

The red soils in most parts of the scheme occur at higher elevations than the 'black cotton' clay soils on which rice is grown. This is the case in Tebere section of the scheme. Here the red soils cover about 900 ha. The red soils are not suitable for rice cultivation because of the unfavourable property of high infiltration rates and the presence of murram or weathering bedrock within a very short distance from the soil surface.

Trials on the irrigation of the red soils were first carried out in the later fifties in Tebere section. These together with the black cotton soils were prepared for basin irrigation. It was later realised that water on the read soils could not be managed properly and efficiently since losses were high. The red soils were then abandoned. In the early sixties red soils were again put under irrigation, applying water on trial basis by furrows and sprinklers. Data on crop yields and farm in-and-out puts were collected. Also some research on the efficiency of water application was done. Most of the data, however, was never evaluated and the research remained inconclusive. Since then, little research has been done on the water losses due to irrigation of the red soils.

At present, the red soils are again being irrigated to a very small scale in the Tebere section. The National Irrigation Board who manage the Mwea Scheme would like to put the red soils in Tebere under irrigated farming. However, there are claims that even in small areas where the red soils are being irrigated, water losses are high and that the excess water infiltrates into the soil and seeps through the subsoil and substratum, causing drainage problems in lower rice growing areas. Due to these drainage problems some rice fields have had to be abandoned. Smedema and Kinyali (1976) assessed the drainage problems likely to occur when the red soils are irrigated on a full scale. They pointed out that the drainage problems in Tebere rice fields arose from deep percolation in the red soils, seepage from canals that run over the red soils, and rainfall. Preliminary investigations by van Alphen *et al*. (1979) showed that canal losses do occur, thus underlining canal seepage as a source of the drainage problems. The main canals that supply water to rice fields in Tebere section run over the red soils for most part of their length.

The objective of the current study has been to investigate the water loss from the red soils of Tebere section by the following methods:

1. Evaluation of deep percolation losses in an area of about 11 hectares of the red soils which is irrigated under horticultural crops and the relation of any losses to the drainage problems in the lower lying black clays of Tebere Units T15 and T19.
2. Measurement of canal water losses in the left branch canal of Tebere section and relation of any losses to the drainage condition of the black clay soils of Units T15 and T19 of Tebere section.
3. Measurement of groundwater dynamics in and around the transition zone from the red soils to the'black cotton' clay soils in Tebere section.

CHAPTER 2

2. LITERATURE REVIEW

2.1. The Water Balance Equation.

In agriclimatology, the soil water dynamics can be assessed at any time by using the water conservation or water balance equation. Under irrigated conditions, the equation can be written as:

$$D = (P + I) - \Delta W - (R + E) \qquad (1)$$

where:

D = deep drainage from the root zone,

ΔW = the change in soil water content in the root zone during a certain period.

P = the precipitation during that period.

I = the amount of irrigation

R = runoff

E = evapotranspiration.

The terms of equation are normally expressed in millimetres. The equation gives an integral form of the water balance, with the various components totalled over a certain period of time. The equation has been widely used in the estimation of evaporation (evapotranspiration) from crops in the field. Such work is documented by Angus (1959), Milthorpe (1960) and McIlroy (1964). The soil water balance can also be expressed in differential form referring to the time rates of the processes, as the rate at which water flows downwards through the lower boundary of the root zone and the evapotranspiration rate. In differential form, the equation is written as:

$$\int_{t_1}^{t_2} \left[(P - R) - (E + V_z)\right] \, dt = \int_{t_1}^{t_2} \int_{o}^{z} \frac{\delta\theta}{\delta t} \, dzdt \qquad (2)$$

where

$(t_2 + t_1)$ = the interval over which the measurements are made (in seconds).
Z = the depth to the lowest point of measurement (in centimetres)
V_z = the net downward flux of water at depth z (in centimetres per second)
θ = the volumetric soil water content
P = precipitation in centimetres per second
R = runoff in centimetres per second
E = evapotranspitation in centimetres per second.

Equations 1 and 2 can be used in determining water balances for continental land masses, hydrological land masses and even for individual plants. In most cases all the elements of equation 1 except E can be measured or estimated and E is then obtained by difference. However, there are several methods of measuring E. The common methods are those of Penman (1948, 1956), Turc (1954), Jensen and Haise (1963), Blaney and Criddle (1950) and Thornthwaite (1948). All these methods employ meteorological data for the computation of potential evapotranspiration. From the value of potential evapotranspiration the crop evapotranspiration can be derived. The method of Penman is widely used and tables which simplify calculations have been prepared by Doorenbos and Pruitt (1977). When the potential evapotranspiration and hence crop evapotranspiration has been determined, the other component that is often difficult to measure is the deep drainage, D. Wilcox (1960) and Hearn and Wood (1964) have observed that any assumptions made of the magnitude of D while solving the water balance equation often introduces serious errors. According to Slatyer (1961), however, when evaporation or evapotranspiration is estimated over short periods, the neglect of the drainage may result in not too serious errors. Knowledge of the drainage term is important in several aspects. It can be used to estimate the downward water losses and hence the water holding efficiency of a soil. Wetselaar (1962) showed the use of the equation in estimating the downward leaching of soluble nutrients especially nitrates. Kelley (1964) has associated the drainage term with the downward leaching of harmful electrolytes from the root zone. The practical problems limiting accuracy in determination of the deep drainage term are fully discussed by Rose and Stern (1965). They have found that there can be detectable upward movement of water even in the absence of a water table. This upward movement of water will greatly affect the value of the deep drainage term. It is therefore important to understand the physical characteristics of the soil profile in question. Gaudet and Valancogne (1976) have also found that deep drainage fluxes and upward capillary fluxes can considerably modify accuracy achieved in solving the water balance equation. Miller and Aarstad (1974) have noted the importance of the deep drainage component in the calculation of the soil moisture depletion rates.

Measurements of precipitation or rainfall is straight forward. However, according to Kittredge (1948), Penman (1963) and Lull (1964), marked differences in the pattern of precipitation actually reaching the ground may develop in many plant communities because of the interception of the precipitation and by vegetation. Subsequently it may be transferred to the soil by channelling down the main stems ('stem flow') or by dripping from the branches, or may be lost by evaporation from the wet surface. Differences also develop in the amount of precipitation reaching the ground between plants, due, particularly, to the disturbed wind structure. The importance of these phenomena in a water balance study depends on the scale of operation. For catchment studies they may be of considerable importance. Slatyer (1962) observed that the amounts of precipitation actually retained on the surfaces and the amounts chanelled down the stems are governed by the morphological characteristics of the species concerned and by the nature of the precipitation. With rain it is usual to observe drip or stem flow after an area rain total of about 2.5 millimetres has been received. Branches and leaves inclined upwards (as in the case with arid zone plants) favour stem flow considerably. Hamilton and Rowe (1949) and Slatyer (1965) have observed that upto 40% of the rainfall incident on an area equal to the horizontal projection of the canopy was chanelled down the main stems and entered the soil with minimal outwash at the bole. The amount of stem flow tends to decrease as wind and rainfall intensity increases. The precipitation that remains on the leaves and stems is always depleted to some degree by evaporation.

Surface runoff further modifies the final pattern of the soil water recharge. Run-off clearly occurs whenever the rate of precipitation exceeds the rate of infiltration and the resultant accumulation of surface water exceeds the pondage capacity at the point of measurement (Slatyer 1966). In consequence, runoff varies with amount and intensity of precipitation (and frequently with duration, since infiltration rate, initially high, tends to decrease with time) and with surface conformation, which determines the degree to which pondage can take place. Minor slope changes modify slope/runoff relationships such that where differences of microtopography exist, changes in run-off can cause spatial vegetation patterning. It is difficult to measure run-off without affecting the run-off pattern over an experimental site. It is frequently measured indirectly through the water balance using equation 1, and either estimating E, or assuming it to be zero. Estimates of ΔW are required before and after run-off inducing rainfalls. If deep drainage term D can be neglected (as is the case in many brief thunderstorms or showers), then run-off is the simple difference between the amount of precipitation and the observed increment in soil water storage.

.Changes in soil moisture storage is normally by sampling randomly within the normal experimental design with an auger. For actively growing vegetation, under moderate evaporation conditions, soil water determination at 2-3 day intervals provide a quantitative picture of crop evapotranspiration. For bare soils, the mechanism of evaporation of soil water, in absence of groundwater has been well studied by Fisher (1923), Pearse et al. (1967) and Wilcox (1960). The effects of wind, temperature or radiation on drying rates has been studied by Hanks et al. (1967). In irrigated conditions, to determine the rates of consumptive use by the soil sampling procedure, it has been customary to take one set of samples following an irrigation, and one or more sets of samples prior to the next irrigation. The first set is taken as soon as the most rapid drainage has occurred and the soil moisture is presumed to be at "field capacity". The rate of consumptive use is then determined by calculating the difference in moisture content between paired sets of samples, and dividing by the interval in days to give the daily rate. It is often questionable when the initial rapid drainage has been completed. Veihmeyer and Hendrickson (1929, 1955) found that comparative equilibrium of moisture content was reached in 2 - 3 days, and considered this a suitable time to take the first samples in moist soils. Corey and Myers (1955), Lewis et al. (1934), West and Perkman (1933) and Wilcox and Mason (1953) all have sampled at anywhere from 1 - 4 days after irrigating, depending on soil texture. Wilcox et al. (1953) however, reported that by taking the first samples at 1 and 3 days after an irrigation, consumptive use values were obtained that were as high as irrigation requirements. Robins et al. (1954) found that sampling at 2 days and 8 days after irrigation gave consumptive use values 23% too high. From literature, therefore, we can see that most workers accepted a sampling time of 1 to 3 or 4 days after irrigation as being suitable for most soils.

The effects of relative moisture content of the soil on consumptive use has also been studied by some workers. Veihmeyer (1927), Veihmeyer and Hendrickson (1955) found that the rate of transpiration was practically the same from the time of irrigation until quite close to the wilting point. Other workers have reported a reduction in transpiration only after two-thirds (Martin, 1940), three-fifths (Wilcox et al., 1953) or even about one-third (Schneider and Childers, 1941) of the available moisture has been used up. Other workers like Bloodworth et al. (1956) and Wilcox and Mason (1933) have found a progressive reduction in the rate of transpiration or consumptive use from immediately after irrigating until wilting. From literature, it appears, therefore, that the results obtained can be influenced not only by moisture content but by other factors such as kind of soil, kind of plant, and root proliferation.

The water use efficiency for a soil can be defined by the term of the water balance equation in question. The terms commonly used in this definition are the run-off, deep drainage and evapotranspiration (Smedema, 1978).

Any of these terms can be expressed as a fraction of the total water input into a soil. Water input either from irrigation or rainfall or both combined. There are several accepted definitions related to irrigation efficiency and the distribution of water over a field that have been given by Christiansen (1947), Hagan et al. (1967), Hart and Reynolds (1965), Howell (1964), Israelson and Hansen (1962) and Bos (1979). In addition Chaudhry (1976), Karmeli (1977) and Karmeli et al., (1978) have suggested that some water distribution patterns are related to specific types of irrigation systems. There have also been derivations of new efficiency and uniformity terms related to these distributions; many of these terms have been applied to the formal evaluations of irrigation performance by Kruse (1978). Researchers still show concern over the proper way to describe performance of irrigation systems. According to Hart et al. (1979), the efficiency and distribution of a particular irrigation can be described through the measurement of as few as four independent quantities, which also allow definition of the irrigation performance and determination of required improvements. These quantities are the volume of water infiltrated in irrigated area (T), the volume of water that infiltrates beyond the required depth (D), volume of available root zone water storage at time of irrigation (i.e. requirement I) and the volume of water deficient after irrigation, which is equal to available root zone water storage after irrigation has occurred (B). From these quantities a relationship exists, thus:

$$T - D = I - B \qquad (3)$$

where the terms are as explained above. Arising from equation 3 are several definitions of irrigation efficiency. Three types of efficiency are of particular significance, that is storage efficiency, deep percolation efficiency and delivery efficiency.

The deep percolation efficiency is defined as the fraction of total water absorbed in the irrigated area that contributes to fulfilling the requirements. It is a measure of the water lost to deep percolation and has a high value (close to 1.0) if deep percolation is low. This gives rise to the equation

$$Ep = (I - B)/T \qquad (4)$$

where Ep is the deep percolation efficiency and I, B and T are as explained in equation 3. For a given irrigation system, acceptable limits of efficiency have been suggested by Hart _et al._, (1979). A minimum allowable value of 0.65 has been suggested. An Ep value equal to or greater than 0.8 is regarded as excellent and values between 0.5 and 0.8 are regarded satisfactory. Ep values less than 0.5 are poor.

2.2. Canal Water Losses

In irrigation water management, conveyance losses result from seepage, leakage through structures; spills due to poor operation of gates and turnouts, evaporation, consumption by weeds and over-delivery due to faulty measurements. The greatest and most common loss, however, is through canal seepage. The remedy for this is normally canal lining. Kraatz (1975) found that a well installed and maintained lining, such as concrete, brick or covered membrane should not lose more than 30 l/m^2 of wetted perimeter per day.

Canal seepage rates are important to irrigation system designers and resource planners will find the average seepage rates helpful in estimating seepage losses for existing or planned systems. Knowledge of these rates will also help in evaluating alternative improvements in water management, such as canal lining programmes, modernising measurement and delivery methods, and installing computer controlled automatic regulation of diversions and deliveries.

Worstall (1976) found that seepage rates varied widely within each broad soil textural class, but the average rates for all the clay loams ranged from 60mm/day in most of his tests. He found no significant linear regression between canal dimension and seepage rates within any one textural group.

Kraatz (1977) has discussed the available techniques of irrigation canal lining. He has emphasized on the need to line small canals and ditches because despite their great importance in the efficient use of irrigation water, they are often neglected by project planners and engineers. The importance of these small channels has also been sounded by Fangmeier and Ramsey (1978). They studied the influence of furrow geometry on the infiltration functions and intake characteristics of irrigation and found that intake rate of a furrow was linearly related to the wetted perimeter for irrigations conducted.

According to Lauritzen and Terrel (1967) seepage rates depend, among other things on:

(i) permeability of the soil,

(ii) existence of natural or artificial linings,

(iii) depth of the water and its velocity and

(iv) elevation of the water table.

In most canals and reservoirs, however, the greatest part of the seepage occurs through relatively short reaches.

Several methods exist of measuring seepage losses from canals. The inflow - outflow method of Robinson and Rohwer (1959) involves the use of a current meter to read the flow of the canal at different points. The method is useful in isolating sections of canal where greatest losses take place. However, in short reaches of the canal and where large volume flows have to be measured, the quantative accuracy of the method may be low. As a result, small differences may be difficult to detect. The ponding method of Rasmussen and Lauritzen (1953) involves sealing sections of the canal with dikes or water tight structures and measuring the rate at which the water elevation in the ponded section lowers with time. This is probably the most accurate way of evaluating seepage losses in short canal reaches. However, ponding interrupts water deliveries and in large canals, involves considerable expenses. Inaccuracies may be due to seepage rates changing from year to year and during the irrigation year, within any reach of the canal.

Seepage meters have been described by Bouwer (1961, 1963). Their use involves the confinement of a small area of the canal perimeter and then measuring the quantity of water passing through it. The meters actually measure the hydraulic conductivity and gradient in the material below the seepage cup. The disadvantage of the seepage meter is that the location of measurement may not represent the section of the canal being measured. Measurements must be made both at the bottom and at the sides of the canal since seepage through these places are different. Rasmussen and Lauritzen (1953) further point out that even when a large number of measurements are made, there is no assurance that seepage meter measurements will provide data that are indicative of losses. According to Bouwer (1963) seepage meter measurements sometimes do give indications of losses at those reaches of the canal where high losses can be expected.

Groundwater elevations can also be used as a qualitative method of detecting seepage. Position of groundwater table in the vicinity of the canal is observed with time. If the groundwater table slopes away from the canal then seepage from the canal can be assumed to be occuring.

The electric logging method developed by the US Department of the interior (1963) is an indicative method for locating those areas in which seepage losses are heavy. The measurement is a continuous one and gives point to point information, although the earth profile needs to be known so that information can be interpreted. The resistance measurement indicates relative saturation of the bed material and the self-induced soil electrical potential indicates the movement of soil water. Measurement with this method can be made with water in the canal. The equipment consists of two lead electrodes connected with wires to a current source, an extremely sensitive voltmeter and track mounted recorders for the readings. The depth to which the resistivity of the formations is measured is controlled by the spacing of the electrodes.

2.3. Groundwater Dynamics

Water table (phreatic surface) observation is a fundamental step in determining the degree and extent of drainage problems of an area. A survey of the water table only will not yield much information because it cannot be treated separately from the other elements with which it is closely connected. For the efficient and effective solution of a drainage problem we also need to know the cause of the problem. The main objectives of a survey of groundwater conditions that forms part of a drainage survey can be defined, according to De Ridder (1974) as:

(a) determining the extent, degree, and nature of existing or potential drainage problems,

(b) analysing the groundwater system and assessing a water balance from which the cause of the drainage problem may be understood, and

(c) indicating how the groundwater system can be altered artificaially so that the resulting water table will not hamper crop growth.

For a survey of groundwater levels or hydraulic head, observations can be made in existing wells, open bore holes, piezometers and surface waters (lakes, streams, canals, etc.). Piezometers are open ended pipes, metal or plastic driven into the ground upto the depth below the surface at which the hydraulic head is to be measured. The water level in the pipe corresponds with the hydraulic head at the pipe's lower end. The pipes may have varying diameters, usually between 2.5 to 8.0 centimeters.

Piezometers are installed both by driving and jetting. Methods of installation have been described in details by De Ridder (1974), Christiansen (1943), Reeve and Jensen (1949) Reger et al. (1950), Donnan and Bradshaw (1952), Mickelson et al. (1961) and U.S. Salinity Laboratory Staff (1954).

The defining equation for hydraulic head comes from a consideration of the law of conservation energy as applied to a liquid system. The equation, known as Bernoulli equation has been explained by Dodge and Thomson (1937) and is also treated in modern texts on fluid mechanics. The equation describes the energy status of a flowing liquid in terms of kinetic, potential and pressure energies. When the energy is expressed as energy per unit weight of water, it has dimensions of length. This length, which is a vertical distance parallel to the gravity force field, is termed "head". For unit weight of water located at a point where the pressure is p, the velocity v, and the elevation above a reference level is z, the "hydraulic head" h, at the point in question in a steady flow system is given by the equation:

$$h = (v^2/2g) + (p/w) + z \qquad (5)$$

where g = acceleration due to gravity and

w = specific weight of water ($w = \rho g$,

where ρ is the density of water)

The individual components of the equation are termed "velocity head" ($v^2/2g$), "pressure head" (p/w) and "position head" (z), representing the kenetic, pressure potential and position potential energies respectively. For flow of water in soils or other porous media, flow velocities are usually very low; and for all practical purposes the velocity head term can be neglected. The hydraulic head equation can then be written as:

$$h = (p/w) + z \qquad (6)$$

The piezometer pipe makes connection with the soil water through the perforated open end of the pipe. In accordance with equation 6 above, the hydraulic head at the lowest end of the pipe is equal to the sum of the pressure head (p/w) and the position head z, or, in other words, it is the height the water level stands in an open pipe above or below a reference elevation. Piezometers have a response time that is not zero because of the volume of water that must move into or out of the piezometer to register a pressure change that occurs in the soil water. The response time depends on the diameter of the pipe, the size and shape of the cavity at the base of the pipe and the hydraulic conductivity of the soil in which the piezometer is placed. For static-hydraulic-head conditions in the soil, the time required for the instrument to register hydraulic pressure of the soil, following a head displacement within the instrument, depends upon the response rate. Hvorslev (1951) found that where hydraulic head in the soil changes with time, there will be a time lag in instrument readings which is also related to the response rate and for which correction should be done.

Frequency of piezometer water level measurements, according to De Ridder (1974), depends on the type of study. In a reconnaissance survey, a frequency of once or twice a month will generally suffice. To get representative data for the water table, all the measurements should as far as possible be taken on the same date of each month. For special investigations, for example the effect of heavy rainfall or excess irrigation on the water table, the instantaneous or gradual rise or fall of the water level in open water courses and their effect on the water table in adjacent land, the transmission of tidal movement in adjacent land and the effect on a water table when a well is pumped, the frequency of measurements can then be done once an hour, or once a day depending on the required level of sensitivity.

CHAPTER 3

3. MATERIALS AND METHODS

3.1. General Information

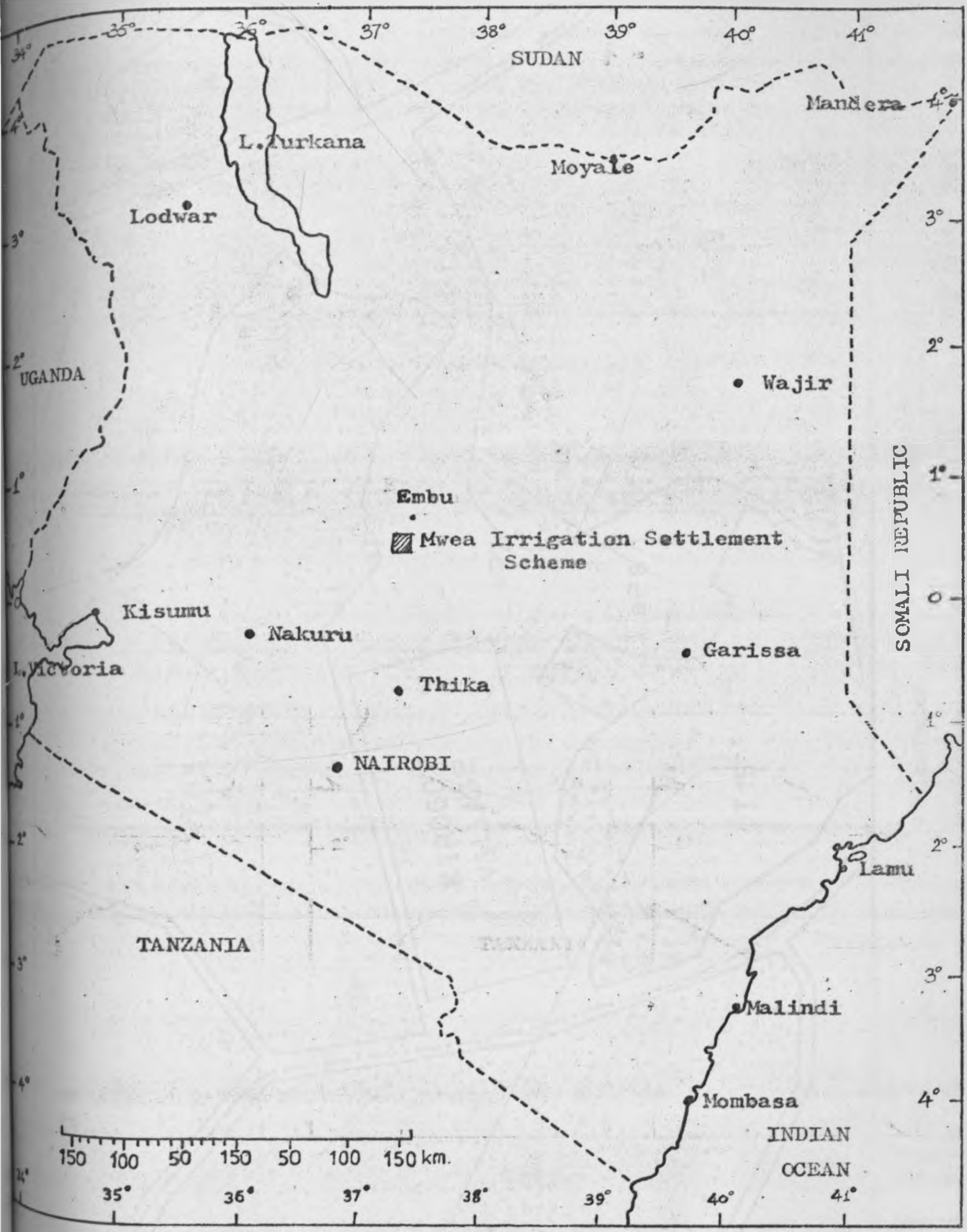
3.1.1. Experimental Site

Mwea Irrigation Settlement Scheme is located in Kirinyaga District of the Central Province of Kenya. It lies approximately between Latitudes 0° 37' and 0° 45' South and Longitudes 37° 17' and 37° 26' East (Map 1) Wanguru, the Mwea Divisional heaquarters is the biggest market centre and the scheme headquarters is located here.

The experimental site is located in the Tebere Section of the Mwea Scheme. A big part of the Unit T15 of the Tebere Section is composed of the Kaolinitic dusky red clays (the red soils). An area of about eleven hectares in this unit, situated behind the settlement village of Kirogo (Map 2) is used as a small scheme where fruits, fruit trees and vegetables are grown under supplemental irrigation. Water for irrigation is abstracted, when possible, from the right branch of the main Tebere canal which passes nearby.

Below the Kirogo village lies a transition zone from the red clay (on the higher parts) to the black clays (in the depression). Seepage spots start at the

Map 1. Map of Kenya showing the location of Mwea Irrigation Settlement Scheme.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35°
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37°
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39°
40°
41°
SUDAN
Mandera
4°
L.Turkana
Moyale
Lodwar
3°
2°
UGANDA
Wajir
1°
Embu
Mwea Irrigation Settlement Scheme
SOMALI REPUBLIC
0
Kisumu
Nakuru
Garissa
L.Victoria
Thika
1°
NAIROBI
2°
Lamu
TANZANIA
3°
Malindi
4°
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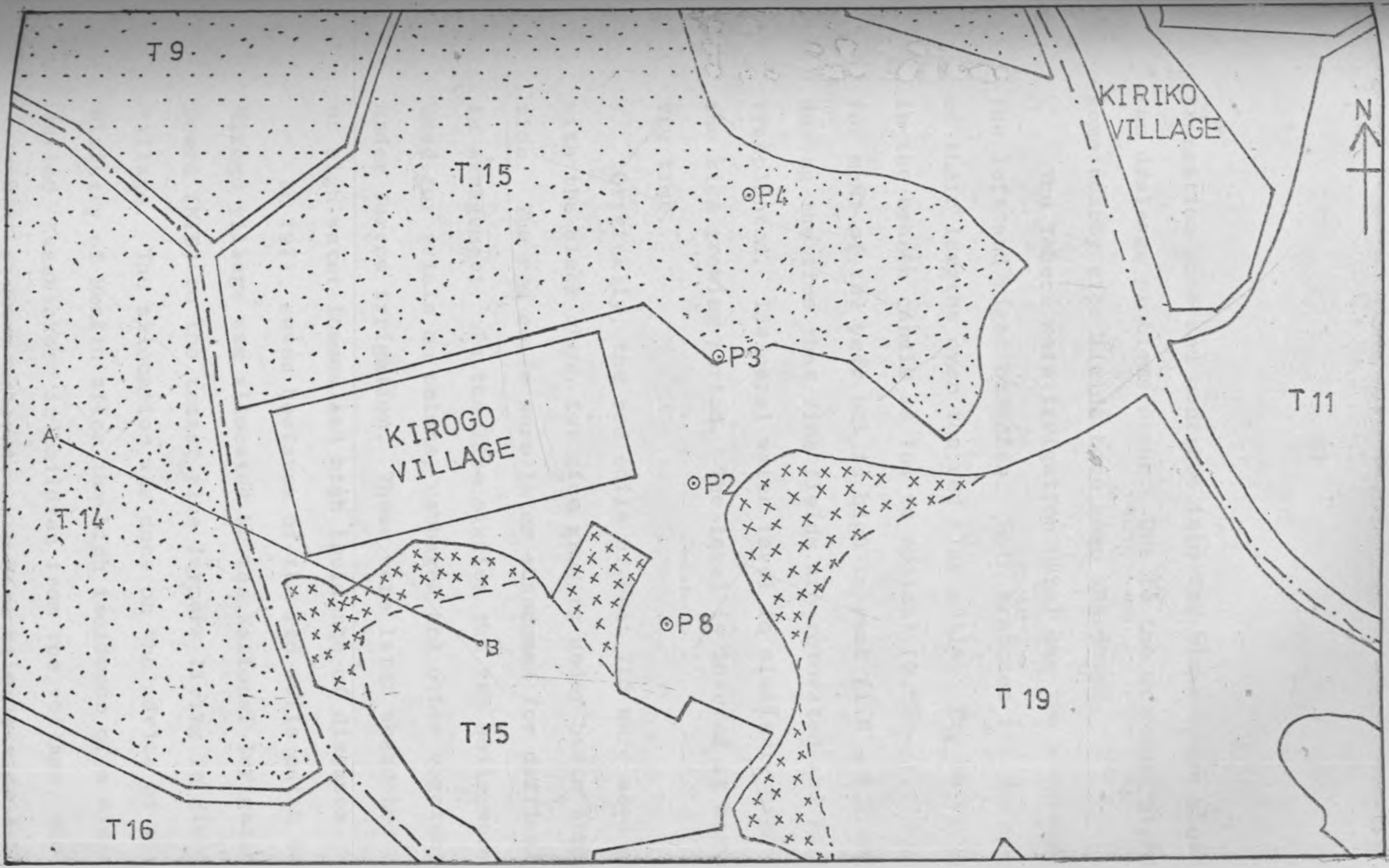


▨ T Red Soils

☐ T Black Clay Soils

⊙ Piezometer

-.-.-.-.- Main Irrigation Canals

SCALE: 1:10,000

Map. 2. The Study Area: Part of Mwea Rice Scheme, Kenya transition zone and continue into the black clays where the drainage problems occur. Due to the drainage problems, some nearby rice fields have been abandoned.

The Tebere main irrigation canal has two branches, the left and right branches. Both branches run for most of their lengths over the red clay soils. The water level in the branch canals is low to optimal (0.85 - 1.1 cumecs) for most of the year but is high to peak (1.6 - 2.1 cumecs) during the time that rice fields are rotovated and rice trasplanted. The canal water level is similarly high during the rice growing period. The level is lowered at harvesting time.

Originally, the red soils of Unit T15 were used along with the black clays, for rice growing under basin irrigation. The red soils were later abandoned for difficulty in management. In the late sixties the red soils were used for trials on onions, cabbages and other vegetables under furrow irrigation. These were later abandoned because of high water losses and high incidence of diseases.

In 1971, seven hectares of the red soils patch behind Kirogo village was allocated by the National Irrigation Board (NIB) to the tenant rice farmers living in Kirogo village. The allocation was done on the advice of the Ministry of Health after the high incidence of a disease called "Kwashiokor" in children from the village, who depended hitherto entirely on a diet of only rice for their daily food. There was, therefore, a great need for proteins and vitamins to be provided for in the diets of the children. The piece of land was alloted by the Village Committee to the farmers on family basis, each family getting roughly one quarter of an acre for growing vegetables and fruits under supplemental irrigation. Not all tenants got a piece of land and later, in 1977, a further four hectares was given out to the remaining tenants. The Ministry of Agriculture offered assistance by assigning a Junior Agricultural Assistant to the area. The assistant would help the farmers in good crop husbandry. Water supply and regulation was left in the hands of NIB staff of the Tebere section.

Today, as many as 15 crops (vegetables, fruits and fruit trees) are grown in the scheme while some parts of the scheme lie fallow due to little or no effort by some farmers. The crops are irrigated only when enough water can flow into the scheme. Even then the irrigation is not scheduled and is done in such a way that too much water is often applied. Frequently, the farmers have to place wooden planks across a drop structure just after the off-take into the vegetable scheme on the right branch canal. This causes excessive water to enter the vegetable scheme, causing overflooding. The farmers usually irrigate their crops during dry periods. During the rainy season, little or no irrigation takes place.

Water also finds way through the scheme into the Kirogo village where it is used for making building blocks out of the red clay soils. The block-making activity and the consequent housebuilding sometimes employs upto 40% of the water intake in the scheme.

The irrigation method in the scheme is, in most cases, by basin flooding and in few cases by furrows. The sizes of the basins range from 6 to 13 square metres. The farmers make the basins and furrows on their strips of land. Scheduling of irrigation on the scheme is not based on any quantified scientific information. Farmers apply water whenever water is available and when they have time, usually in the afternoons. This they do when they notice the soil surface cracking after drying or when the crops show symptoms of wilting.

Crop husbandry in the scheme follows a traditional pattern. Farmyard manure, wood ash and rice husks are incorporated into the soil before, during or after land preparation. The land preparation is done using hoes and to a very limited extent, ox-drawn ploughs. When the ground surface is hard (during the dry season), the farmers often apply irrigation water to the plots to make the ground soft. Chemical fertilizers are not used in the vegetable scheme. Weeds are controlled manually using 'pangas' and hoes. Pest control is minimal, practiced mostly by farmers who grow cabbages and tomatoes.

3.2. Methods of Study

3.2.1 Inventory of Soil Properties

Three soil profile pits were dug in the experimental site; two in the red soils and on a black clay soil spot (Map 2). The pits were described according to the (F.A.O. guidelines (1977) and sampled accordingly for the determinations described below.

3.2.1.1. Physical Characteristics

3.2.1.1.1. Particle size analysis

Disturbed soil samples were taken from the soil profile horizons. The samples were dried at 40 - 45°C in the laboratory and the fraction with diameter of 2.0 mm and below was used for particle size analysis by the hydrometer method of Bouyoucos (1951) as modified by Day (1965).

Fourty five grams of 'Calgon' (sodium hexametaphosphate) and five grams of sodium carbonate were dissolved in distilled water and the solution diluted to a volume of 1.0 litre. This gave a 5% 'calgon' solution. The Bouyoucos hydrometer used for particle size analysis was first calibrated by adding 50ml of 'calgon' solution to a sedimentation cylinder and then adding distilled water to make exactly 1.0 litre. The suspension was mixed thoroughly with a plunger, the room temperature having been recorded. The hydrometer was then lowered into the suspension carefully and the scale reading, R_b, at the upper edge of the meniscus surrounding the stem noted.

Fifty grams of the 2.0 mm dry soil was weighed and put in a plastic bottle. A similar amount was used for determination of oven-dry weight. The latter was dried overnight in an oven at 105°C and then reweighed. 300 ml. of water, followed by 50 ml. of 5% 'calgon' was added and the bottles were closed and mounted onto an end-over-end shaker, which is electrically driven. The power was turned on and the samples allowed to shake for about 15 hours.

The soil suspension was thereafter transferred, with the aid of a jet of water from a wash bottle, into a 1000 ml. graduated cylinder and made upto the mark with water. The suspension was mixed thoroughly with a plunger for one minute and the time when stirring ceased was recorded. The hydrometer was carefully placed into the suspension and the hydrometer reading, R, taken 40 seconds after stirring ceased. The reading and the temperature of the suspension was recorded. This reading (R) was used to determine silt plus clay content of the suspension.

After exactly six hours from the time stirring ceased, a second hydrometer and temperature reading was taken for both soil suspension and blank. This second reading was used as the basis for determining the clay fraction.

When a blank was used, correction for both temperature and dispersing reagent were affected simultaneously. The corrected reading gives the concentration C of the suspension in grams per litre using the equation:

$$C = R - R_b \qquad (7)$$

where C = concentration in grams per litre

R = hydrometer reading of the soil suspension.

R_b = hydrometer reading of the blank solution.

The summation percentage values were calculated using the equation:

$$P = 100\ (C/C_o) \qquad (8)$$

where P = summation percentage

C = concentration as obtained from equation 7.

and Co = oven dry weight of the soil in grams per litre of suspension.

The concentration percentage at the end of 40 seconds is the percentage of material still in the suspension at the end of that period, that is, silt plus clay. This percentage was subtracted from 100% and was recorded as the percentage of sand. The concentration percentage at the end of 6 hours is the percentage of 0.002mm clay. The percentage of silt was obtained by subtracting the sum of the percentages of sand and clay from 100%. The texture classification was done using the United States Department of Agriculture (U.S.D.A.) texture triangle (Appendix A15).

3.2.1.1.2. Saturated Hydraulic Conductivity of Soil Cores and Bulk Density

Soil cores were obtained in metal rings fitted into a core sampler which can be driven into the soil using a hammer. The average size of the rings used to take the undisturbed cores was 5.2 cm. in height and 5.0 cm. in diameter. The samples were taken from all the horizons of all the pits. Eight core samples were taken from each horizon, four horizontally and four vertically. Care was taken to avoid compaction of the soil cores.

In the laboratory, the bottom of each core was capped with a cheese close filter. The exposed end of the core was connected to another empty ring of the same size as the plastic tape and then placed in a large plastic tray. The cores were saturated with water at room temperature by raising the water level in the tray slowly upto 1.o cm below the top of the cores and then allowed to stand for some time. The cores were then carefully mounted vertically and supported on a porous outflow surface. A shallow water level of 3.0 cm. depth was maintained over the soil surface by a siphon tube from a constant level reservoir. The water flowing through each core with time was collected in a beaker and measured. The hydraulic conductivity of the soil was calculated using the equation:

$$K = (Q/At)/(L/\Delta H) \qquad (9)$$

where K = hydraulic conductivity in cm./hr.

Q = the volume of water passing through the core in millilitres.

t = time in hours.

L = length of the soil core in centimetres.

A = cross sectional area of the core in square centimetres.

ΔH = hydraulic head difference causing the flow.

The cores used in determining hydraulic conductivity were also used in determining bulk density. The mass of each core was determined after drying to a constant weight in an oven at 105°C and the volume was that of the sample as taken in the field. The bulk density of each core was calculated using the equation:

$$\rho_B = M_s/V_t \qquad (10)$$

where ρ_B = bulk density

M_s = weight of oven dry core,

and V_t = the field volume of the core.

The bulk density was expressed in grams per cubic centimetres, and is numerically equal to the apparent specific gravity or volume weight.

2.3.1.1.3. Water Retention and Water Release

Soil core samples for the determing water retention and release were taken using the same procedure used to sample for hydraulic conductivity and bulk density. For water retention and release at high suction values (5 to 15 bars), disturbed samples were taken from the horizons. Five samples were taken per horizon.

After the core samples were saturated and allowed to equilibrate at room temperature, the rings were wiped and the weight at saturation taken. The samples were then placed in a pressure plate apparatus. After placing the cores on a ceramic plate and making the appropriate connections, the apparatus was closed and adjusted for the required suction values.

For the disturbed samples, rubber rings were placed on an appropriate ceramic plate in a pressure plate apparatus and the rings filled with soil. Each soil sample was replicated five times. The soil in the rings were then saturated with water and allowd to stand for about half an hour. The apparatus was then closed and the appropriate suction applied. The suctions applied to the cores were 0.1, 0.2, 0.5 and 1.0 bars while to the disturbed samples, 5, 10 and 15 bars. The approach to equilibrium was followed by connecting the outflow tube from each plate to a graduated cylinder and recording the readings occasionally. When equilibrium was reached the air pressure was released, the samples removed and weighed. Two types of ceramics were used, one for tensions upto 1.0 bar and the other for tensions upto 15.0 bars.

Soil water retention (in volumetric water content, cm^3/cm^3) in each sample was calculated using the following equation:

$$\theta = (W_{t(i)} - W_{t(OD)}) / (Vs) (\rho_w) \qquad (11)$$

where θ = volumetric water content,

$W_{t(i)}$ = weight of the soil sample in grams at corresponding soil water suction,

$W_{t(OD)}$ = oven-dry weight of the sample in grams,

V_s = volume of the soil in cm.^{3} as from the field,

ρ_w = density of water expressed in grams/cm.^{3}.

Soil water release data was determined from the same samples used for determination of soil water retention using the following equation:

$$W_{(T)} = (W_{t(o)} - W_{t(T)}) / (V_{s(o)}) (\rho_w) \qquad (12)$$

where $W_{(T)}$ = soil water release equivalent to volume fraction of water occupying space in soil and now, at suction value T is released by the soil,

$W_{t(o)}$ = initial weight of soil in grams at saturation,

$W_{t(T)}$ = soil subsequent to weighing in grams at corresponding value of suction T,

$V_{s(o)}$ = volume of the soil as from the field in cm^3,

ρ_w = density of water expressed in grams/cm^3.

2.3.1.1.4. Infiltration Rate Measurement

The infiltration measurements were taken during the dry period to represent conditions when irrigation is most suitable. The measurements were done on plots with various surface conditions as follows: non-used non-ploughed (fallow), only ploughed and/or recently planted and earlier planted plots.

The measurements were done using double ring constant head method. The double ring method was done by driving two concentric metal cylinders into the ground to a depth of 15.0 cm. The inner cylinder had a diameter of 32.0 cm. Water from a plastic tank arrangement was kept in the space between the cylinders at more or less a constant head. The water in between the two cylinders acted as a buffer, keeping the infiltration in a vertically downward direction. Reading of the water level in the tank was noted at intervals of five minutes, starting from the time when the first drop of water was put into the inner cylinder to the time when the water stopped leaving the tank into the inner cylinder. A rubber float with a graduated stem (in centimetres), kept in position by a metal clip, was used to ascertain constant head of water in the inner cylinder.

Cumulative infiltration rate (I_{cum}) was expressed using the Kostiakov equation:

$$I_{cum} = at^n \qquad (13)$$

where I_{cum} = cumulative infiltration,

a = constant for a given soil,

n = constant for a given soil moisture content,

and t = the time of infiltration.

The average infiltration, which is the relatively constant rate of infiltration that develops after 3 to 4 hours was plotted and determined for each site.

3.2.1.2. Chemical Characteristics

The initial soil samples from the soil profile horizons were analysed chemically for pH, available nutrients, cation exchange capacity (CEC), electrical conductivity and exchangeable bases.

The soil pH was determined potentiometrically on a direct reading pH meter with glass electrodes using 1:1 and 1:2½ soil to water suspensions. The pH was also measured of a 1:2½ soil to 0.1N potassium chloride suspension.

The available nutrients were determined in a mass method using the double acid (0.05N HCl and 0.025N H_2SO_4) extration technique developed by Mehlich *et al.* (1962).

By the method, 5.0 grams of soil, 250 mg. of charcoal and 25 ml of the extracting solution were shaken for 10 minutes The acid replaces the bulk of the exchangeable metal cations and the sulphate anion is exchangeable for the phosphate. Phosphorus, magnesium and manganese were determined colorimetrically. Reagents were added to the soil extracts to develop characteristic colours. The optical density of the yellow phosphorus solution was read on the colorimeter using a blue filter, red magnesium using a green filter and violet manganese using a dark green filter . The concentrations of the samples were read from standard curves. Sodium, potassium and calcium were determined on a flame photometer. Aliquots of the soil extracts from which interfering phosphate and sulphate ions had been removed by an anion exchange resin were used. The flame photometer readings were taken using the appropriate filters. Concentrations of the samples were determined using the standard curves.

Organic carbon was determined by the titration method of Peach _et al_. (1947) as modified by Mehlich _et al_. (1962) using potassium dichromate and ferrous ammonium sulphate. Total nitrogen was determined by the modified semi-micro Kjeldahl method in which finely ground soil is digested with concentrated H_2SO_4 in fume cupboard, using a mixed catalyst. An aliquot containing nitrogen as ammonium sulphate was transferred to the distilling flask and made alkaline with sodium hydroxide. Ammonia was distilled off, collected in boric acid-mixed indicator solution and titrated against standard acid to a pink end point.

Cation exchange capacity was determined by the calcium saturation method of Rich (1961). Exchangeable calcium, magnesium and potassium were determined by N NaOAc (pH 7.0) extraction and their concentrations measured by atomic absorption spectrophotometer. Electrical conductivity was measured of a 1:2½ soil to water suspension.

3.2.2. Evaluation of Deep percolation Efficiency in Kirogo Vegetable Scheme

In the evaluation of deep percolation efficiency, the deep percolation losses were taken as the yardstick for the water use efficiency. The higher the deep percolation, the lower the efficiency of water use and vice versa. The deep percolation was determined as the unknown in the following water balance equation:

$$D = (P + I) - \Delta W - (R + E) \qquad (14)$$

where D = deep percolation (seepage),

P = rainfall or precipitation,

R = surface drainage (runoff),

ΔW = the change in soil moisture storage over the measuring period,

E = the evapotranspiration,

and I = the amount of irrigation water applied.

In equation 14 above, all terms except D were measured and/or estimated. I and R were measured by means of a rectangular and V-notch weirs respectively. P was measured by means of a rain gauge installed in the scheme. ΔW was determined as the difference in soil moisture storage between the beginning and the end of the measuring period. The soil moisture content was determined gravimetrically on samples taken at depth intervals upto 180cm. One hundred sites distributed over the scheme were sampled for each moisture determination.

The water balance was done during one year over three different seasons; dry season (full time irrigation), short rains (supplemental irrigation) and long rains (little or no irrigation).

At the beginning 100 sites were sampled with depth for initial moisture content (average) of the scheme soil. A crop survey was also done to find the percentage occupancy of the scheme by different crops. For this purpose, the scheme was divided as follows: fraction occupied by short crops, fraction occupied by tall crops and the fallow portion. Water was then applied to the scheme, the amount applied being measured by a rectangular weir installed at the scheme inlet. At the end of the measurements a crop survey was done again to monitor any changes in the cropping pattern. The soil moisture content (final) was determined by sampling at another 100 sites distributed all over the vegetable scheme. Runoff water or any water leaving the scheme at the lower end was measured using a V-notch weir. Rainfall and pan evaporation data were also collected at the scheme during the same period. A water balance was then done for a whole scheme and the amount of water lost by deep percolation worked out. The deep percolation efficiency was then calculated.

3.2.3. Canal Water Losses

Two points were chosen on the left branch canal of the Tebere section for measurement of canal water losses. The points chosen were at a distance of about 1.0 km. The points were chosen such that there was no off-take structures between the two points at whcih comparative flow measurements were taken. The sides of the canal at the points of measurement were then streamlined by cutting the weeds along the canal sides and straightening the edges for a distance of ten metres on either side of the measuring point.

The measuring points were located in cross-sections taken at right angles to the flow of the canal. First a wooden bridge was placed across the point of measurement. The width of the canal at that point was measured and recorded. The width of the canal was then subdivided into a number of gauging stations. The distance between any two stations was at most 20 cm. The depth of water at the various stations was measured. One fifth, one half and four fifths of the depth at every station were then calculated. The "OTT' propeller type current meter was then assembled and the rotating part connected to the counter. Current meter readings were then taken, revolutions of the meter propeller at every station being recorded after 30 seconds. Readings were taken for every station at 0.2, 0.5 and 0.8 of the depth in centimeters. During the measurements it was ascertained that the canal water level was constant. This was done by installing a staff gauge at the point in the canal and noting the water level reading on the gauge every five minutes.

3.2.4. Groundwater Dynamics

Groundwater pipes (piezometers) were installed along a line starting from the red soils, through the transition zone from red to balck clay soils, into the black clay soils. The pipes were installed at positions as indicated on Map 1.

Suitable sites were selected along the slope from red to black soils. Auger holes were made at the selected sites and the soil profile studied during the boring. The holes were made until the groundwater was stricken but some were also made to a point before the groundwater.

A long plastic pipe of 3.0 cm. diameter (the lowest 30cm perforated and covered with nylon cloth) was placed in the auger hole. Coarse sand was put in the auger hole through the side of the pipe to cover completely the bottom 30 cm. around the perforated (covered) portion. The soil material from the auger hole was then used to fill the rest of the space around the pipe, compacting the soil with the stem of an auger as it was placed into the hole. Wet concrete was then used to seal the top part of the auger hole around the pipe so as to prevent any water going into the auger hole. The pipe was then cut to leave about 30 cm. of it above the ground level. A security device (cylindrical iron tube of 15 cm diameter which had a screw top, which can be locked) was installed to cover the pipe. Concrete was used to fix the security device around the pipe. The security device was locked and the whole system was left for two days to allow the concrete to set and for the groundwater in the pipe to stabilize. Readings of groundwater level were taken by a brass sounder. The readings were taken daily beginning in February 1979 upto February 1980. The time interval (one year) enabled groundwater fluctuations to be monitored through the dry and rainy seasons, through periods of low or high canal water levels and through periods of none or intensive irrigation in the vegetable scheme.

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1. Characteristics of the Mwea Soils

Some physical and chemical properties of the Mwea red and black soils have been presented in Tables 1, 2 and 3 and in Fig. 1-6 and Append. A1-A4. Summary of field observation of the red soils is presented in Appendices A5 and A6. The Mwea red soil has a clay texture, with silt and sand fraction decreasing with depth to the weathering volcanic tuff bedrock. The presence of an argillic horizon indicates the maturity of the soil with illuviation and weathering in the profile. The Mwea black soil has a clay texture with clay fraction over 66% throughout the profile. The sand and silt fractions are more or less constant down the profile. The hydraulic conductivities (Appendix A4) of the core samples have been classified according to O'Neal (1952) as given in Appendix A7. The conductivity values are highest for the top soils reducing in value with increasing depth. The reason for the hydraulic conductivity being so high in the top soil' is because of the development in the top soil of a granular fine and medium structure of a moderate grade and hence the presence of many macro- and bio- pores. The subsoil exhibited lower hydraulic conductivity because of the clay concentration which is evident from the texture

Table 1. Some physical and chemical properties of the Mwea Soils

Soil property	Unit	Red Soil Horizon (Pit 2)					Black soil Horizon	
		0-25 cm	25-48 cm	48-125 cm	125-195 cm	195-239+ cm	0-28 cm	28-100+ cm
Sand	%	14	14	12	12	14	18	15
Silt	%	38	36	26	22	18	16	16
Clay	%	48	50	62	66	68	66	69
Texture	clay	clay	clay	clay	clay	clay	clay	clay
PH-H_2O 1:2½ susp.		6.0	5.6	5.7	5.4	5.1	5.8	7.8
pH-KCl 1:2½ susp.		5.0	4.7	4.7	4.7	4.5	5.0	6.3
pH-Sat. ext.		5.6	5.3	5.3	5.1	4.8	5.6	7.2
O.M.	%							
CEC	meq/100g	31.0	28.2	22.5	24.8	25.2	44.0	55.5
Exch. Ca	meq/100g	12.85	10.80	7.3	4.85	4.85	15.3	33.3
Exch. Mg	meq/100g	6.80	5.45	5.20	5.0	5.0	10.14	18.51
Exch. K	meq/100g	2.52	1.59	0.75	0.29	0.30	0.65	0.87
Exch. Na	meq/100g	0.60	0.70	0.35	0.45	0.26	1.74	1.98
Avail. Mn	meq %	1.06	0.82	0.74	0.74	0.82	0.28	0.32
Avail. Na	meq %	0.16	0.24	0.06	Trace	0.04	1.87	1.59
Avail. K	meq %	1.08	0.64	0.26	0.10	0.08	0.36	0.22
Aval. Ca	meq %	8.0	7.2	1.9	0.6	0.4	13.8	16.0
Avail. Mg	meq %	7.9	6.0	8.6	5.2	6.4	8.1	17.0
Avail. P	ppm	220	194	234	68	58	222	227
Avail. N	%	0.11	--	--	--	--	--	--
C	%	1.47	0.98	0.65	0.22	0.26	1.87	--
EC 1:2½	mmhos/cm.	0.08	0.07	0.06	0.03	0.03	0.78	0.70

O.M. = Organic Matter; Exch. = Exchangeable; Avail. = Available;
susp. = suspension; Sat. extr. = Saturation extract.

Table 2. Some physical and chemical properties of the Mwea soils

Soil property	Unit	Red Soil Horizon (Pit 1)				Black soil Horizon	
		0- 25cm	25-48cm	48-106cm	106-150+cm	0-28cm	28-100+cm
Sand	%	16	14	12	12	18	15
Silt	%	38	32	28	24	16	16
Clay	%	46	54	60	64	66	69
Texture		Clay	Clay	Clay	Clay	Clay	Clay
pH-H_2O 1:2½ susp.		5.8	5.6	5.9	6.2	5.8	7.8
pH-KCl 1:2½ susp.		4.9	4.8	4.5	5.4	5.0	6.3
pH-sat. extr.		5.8	5.8	6.1	6.0	5.6	7.2
O.M.	%						
CEC	meq/100gm.	31.4	28.2	26.2	25.6	44.0	55.5
Exch. Ca.	meq/100gm.	14.58	12.05	11.90	10.50	15.3	33.3
Exch. Mg.	meq/100gm.	7.05	6.05	6.45	6.05	10.14	18.51
Exch. K	meq/100gm.	2.68	1.22	1.26	1.30	0.65	0.87
Exch. Na.	meq/100gm.	0.70	0.45	0.45	0.35	1.74	1.98
Avail. Mn.	meq. %	0.73	0.42	0.76	0.90	0.28	0.32
Avail. Na	meq %	0.12	0.08	0.08	0.12	1.87	1.59
Avail. K	meq %	1.12	0.36	0.42	0.65	0.36	0.22
Avail. Ca	meq %	14.6	6.2	8.6	8.0	13.8	16.0
Avail. Mg	meq %	6.9	4.1	5.8	5.6	8.1	17.0
Avail. P	ppm	416	312	436	240	222	227
Avail. N	%	0.10	-	-	-	-	-
C	%	1.14	1.22	0.68	0.68	1.87	-
EC 1:2½	mmhos/cm	0.09	0.06	0.07	0.07	0.78	0.70

O.M. = Organic matter; Exch. = Exchangeable; Avail. = Available;
susp. = suspension; sat. extr. = saturation extract.

Fig. I. Relationship between volumetric water content(%) and soil water suction in bars for the Mwea red soil profile I.

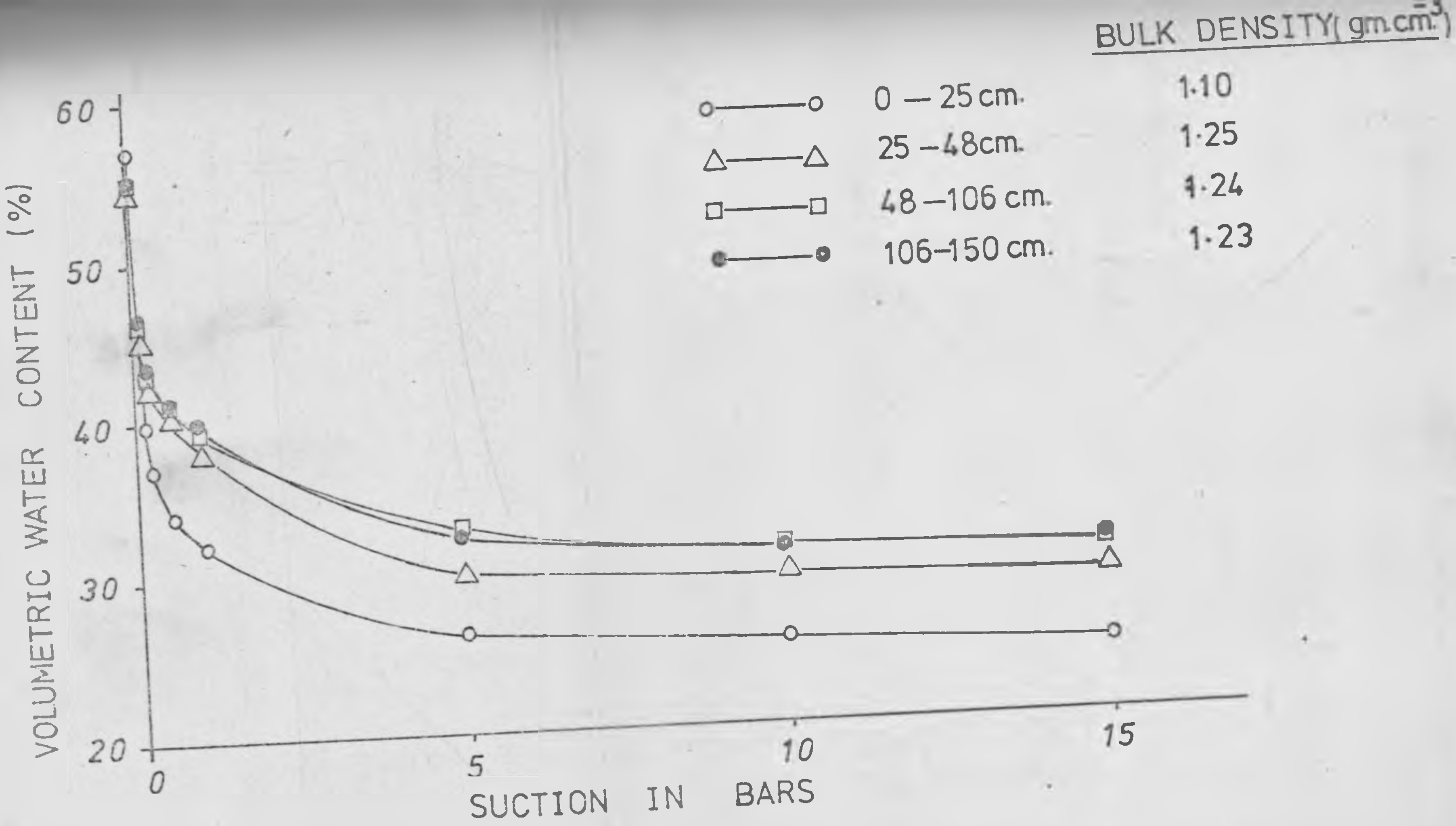
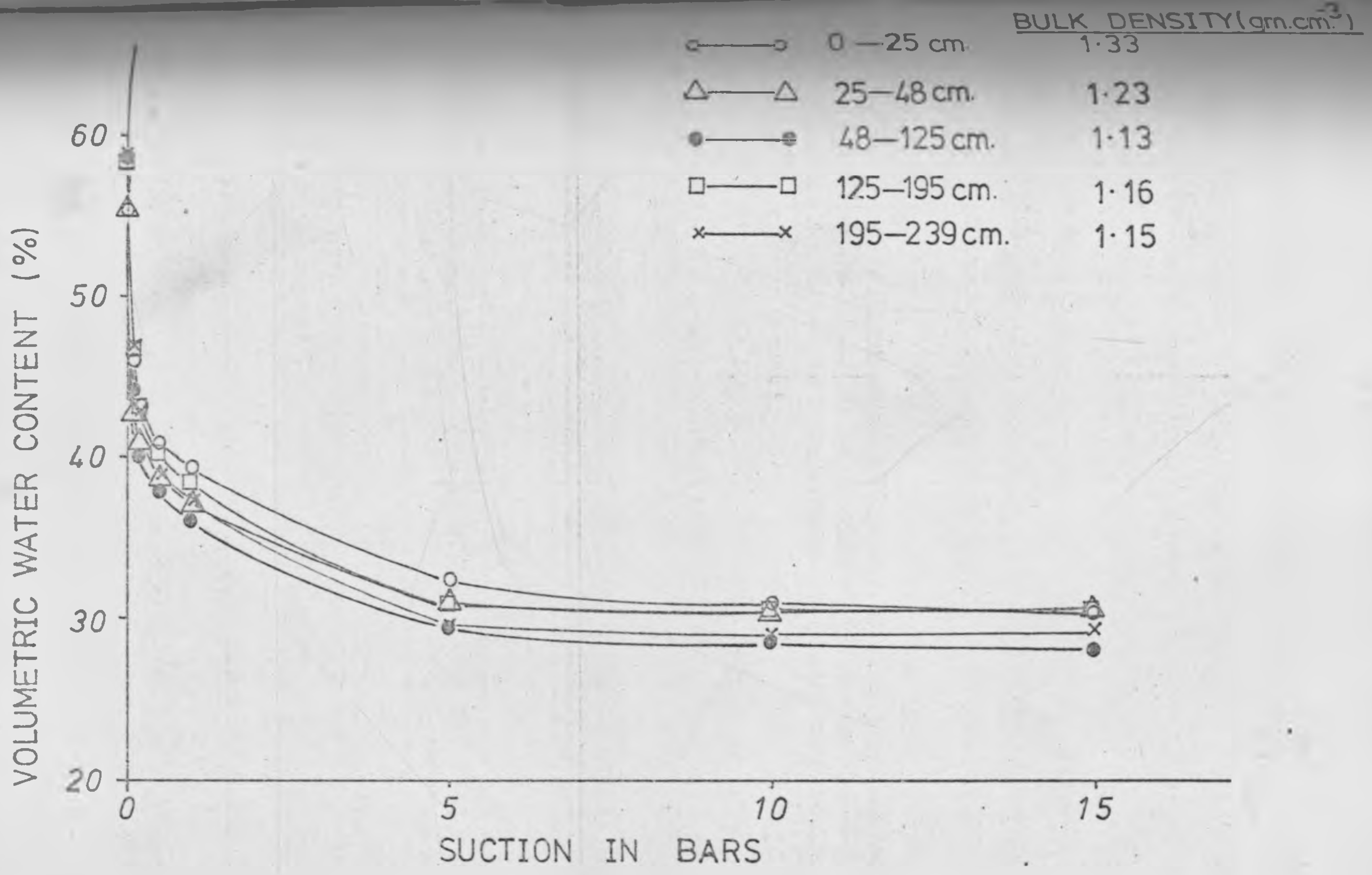
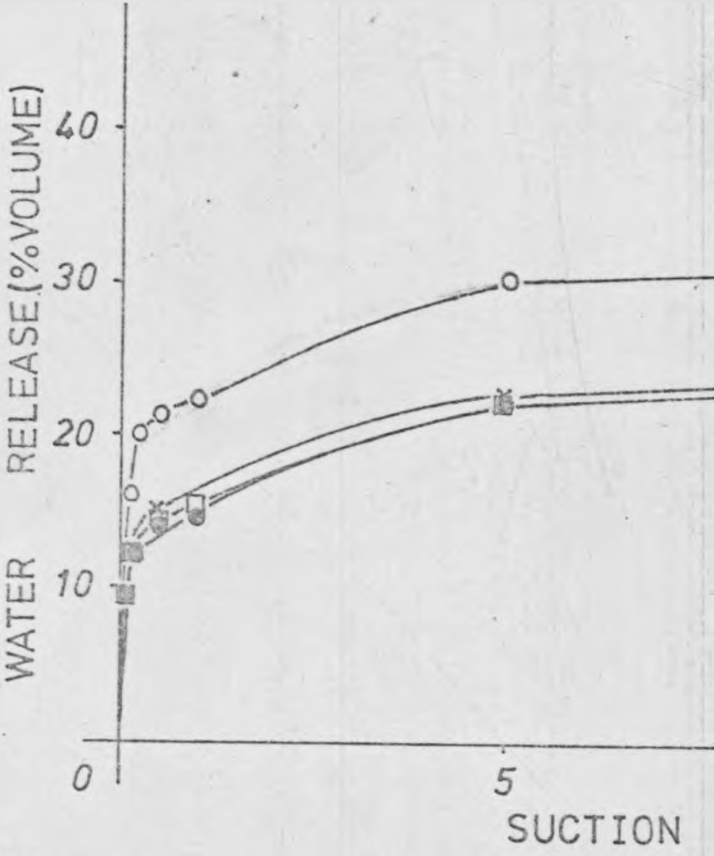

BULK DENSITY(gm.cm⁻³)
0 — 25 cm. 1·10
25 — 48cm. 1·25
48 — 106 cm. 1·24
106–150 cm. 1·23
VOLUMETRIC WATER CONTENT (%)
60
50
40
30
20
0
5
10
15
SUCTION IN BARS

Fig.2. Relationship between volumetric water content(%) and soil water suction in bars for the Mwea red soil profile II.



BULK DENSITY(gm.cm^{-3})
0 —25 cm 1·33
25—48 cm. 1·23
48—125 cm. 1·13
125—195 cm. 1·16
195—239 cm. 1·15
VOLUMETRIC WATER CONTENT (%)
60
50
40
30
20
0
5
10
15
SUCTION IN BARS

Fig.3. Relationship between water release (%volume) and soil water suction in bars for the Mwea red soil profile I.


WATER RELEASE (%VOLUME)
40
30
20
10
0
5
SUCTION

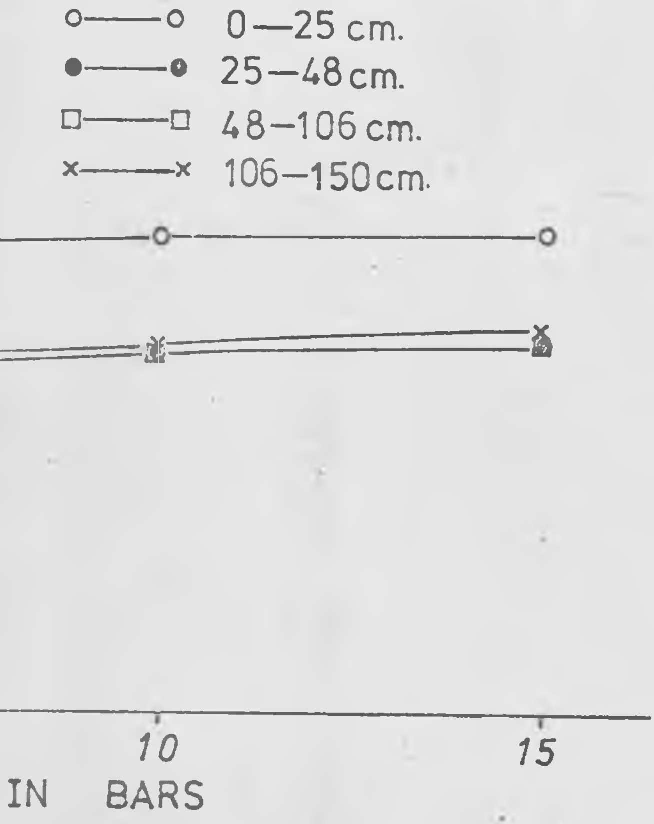
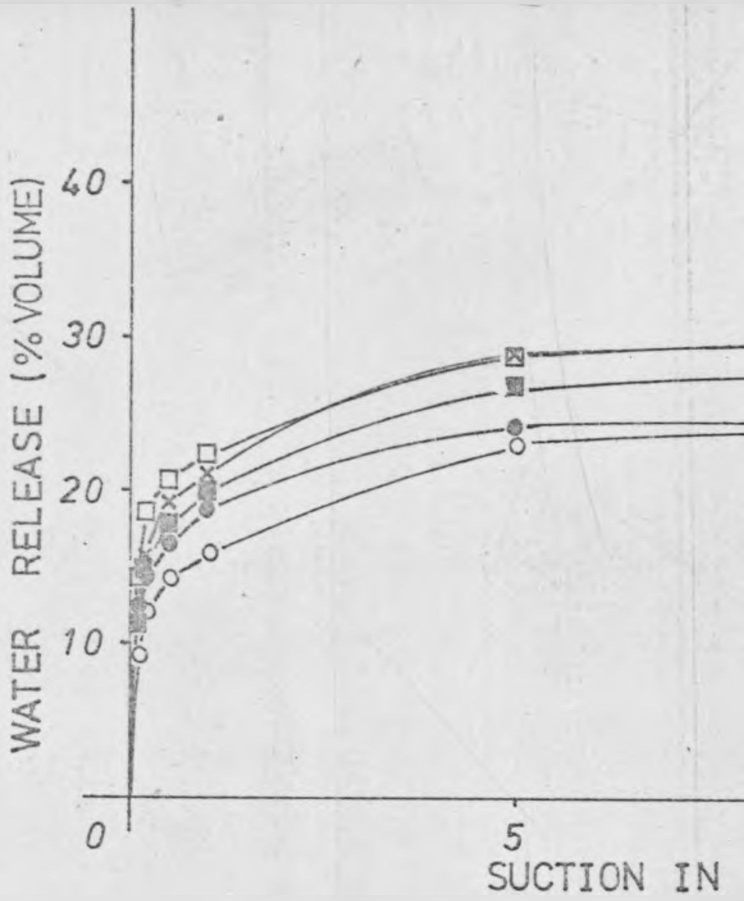

0—25 cm.
25—48 cm.
48—106 cm.
106—150 cm.
10
15
IN BARS

Fig.4. Relationship between water release (% volume) and soil water suction in bars for the Mwea red soil profile II.


WATER RELEASE (% VOLUME)
40
30
20
10
0
5
SUCTION IN

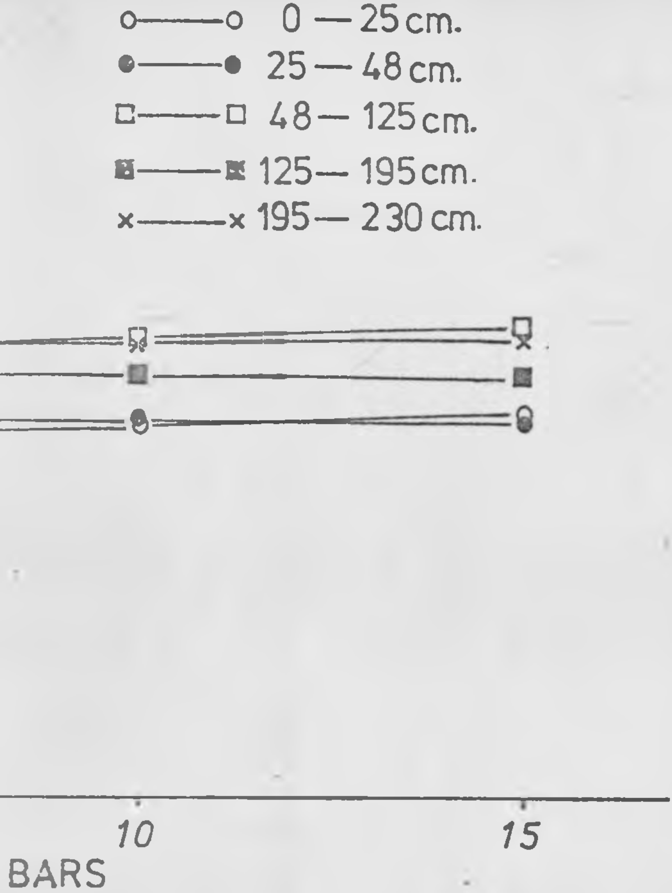
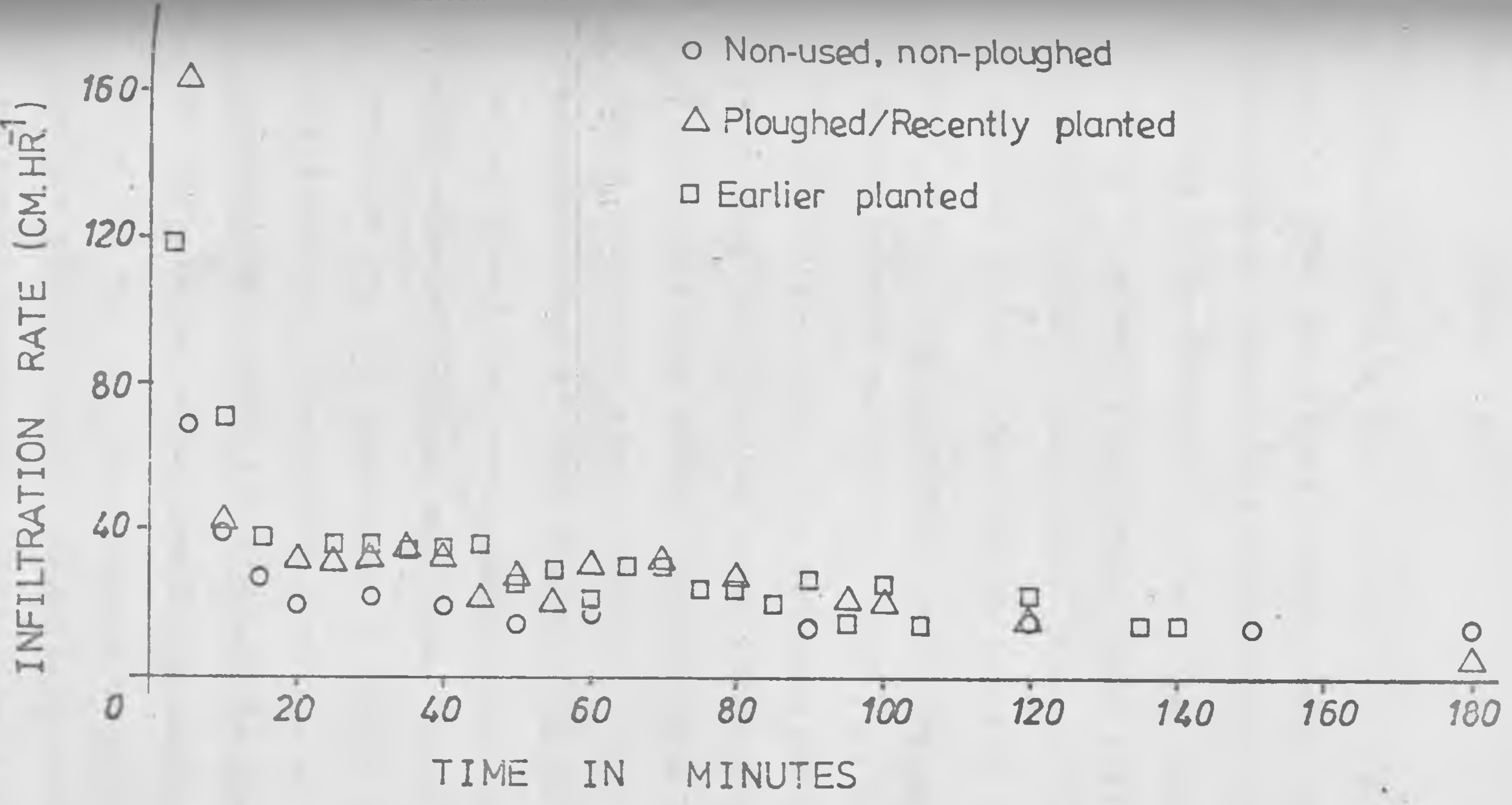

○——○ 0 — 25 cm.
●——● 25 — 48 cm.
□——□ 48 — 125 cm.
■——■ 125 — 195 cm.
×——× 195 — 230 cm.
10
15
BARS

Fig.5. Relationship between infiltration rate ($cm.hr^{-1}$) and time in minutes for three different surface conditions of the Mwea red soils.


○ Non-used, non-ploughed
△ Ploughed/Recently planted
□ Earlier planted
INFILTRATION RATE (CM.HR^{-1})
160
120
80
40
0
20
40
60
80
100
120
140
160
180
TIME IN MINUTES

analysis (Table 1).

The basic infiltration rates (Appendix A3) are plotted on Figure 5, for the three types of soil conditions of the Mwea red soils. The earlier planted sites (Plot C) showed the highest basic infiltration rates of the three soil conditions. This was probably because the earlier planted plots had no limiting layer as the roots had penetrated any plough layer that may have been formed during ground preparation. The root channels enable water to infiltrate fast. The non-used non-ploughed sites showed higher infiltration rates than the ploughed and/or recently planted sites. The non-used sites had no disturbance except for minor trampling which rendered them slightly compact. The ploughed and/or recently planted sites showed the lowest infiltration rates. This was probably due to the fact that these sites had just been prepared and the presence of a plough layer hampered infiltration. Classified according to the system of Rickard and Cossens (1966) given in Appendix A8, the earlier planted sites showed high infiltration rates while the non-used non-ploughed sites had medium rates and the ploughed and/or recently planted sites showed low rates. Cumulative infiltration (in cm.) plotted against time in minutes shown on Fig. 6 shows that the fallow (non-used, non-ploughed) sites and the earlier planted sites both had constantly increasing infiltration

Fig.6. Relationship between Cumulative Infiltration(cm.) and time in minutes for three different surface conditions of the Mwea red soils.

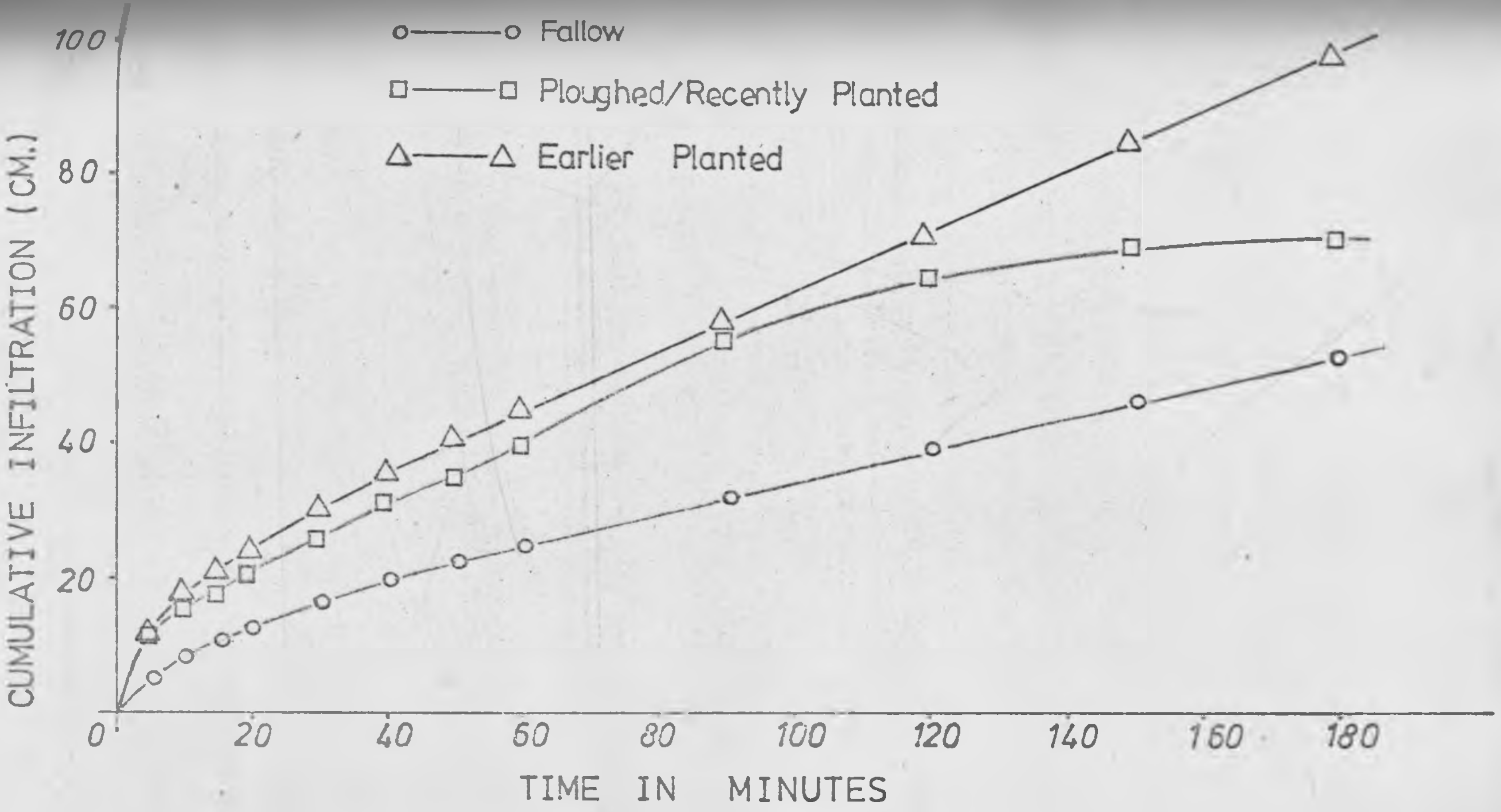
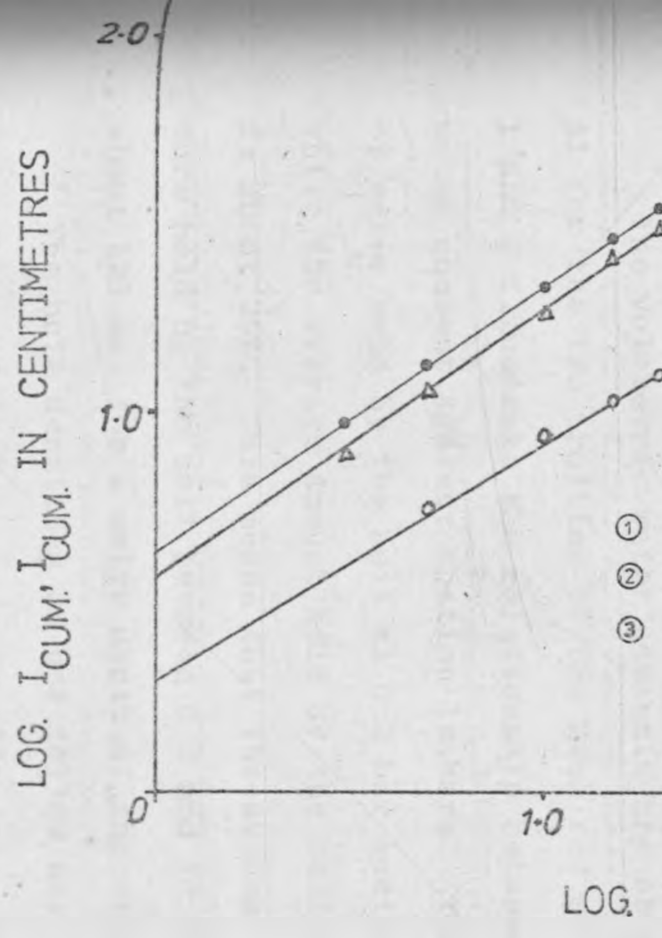
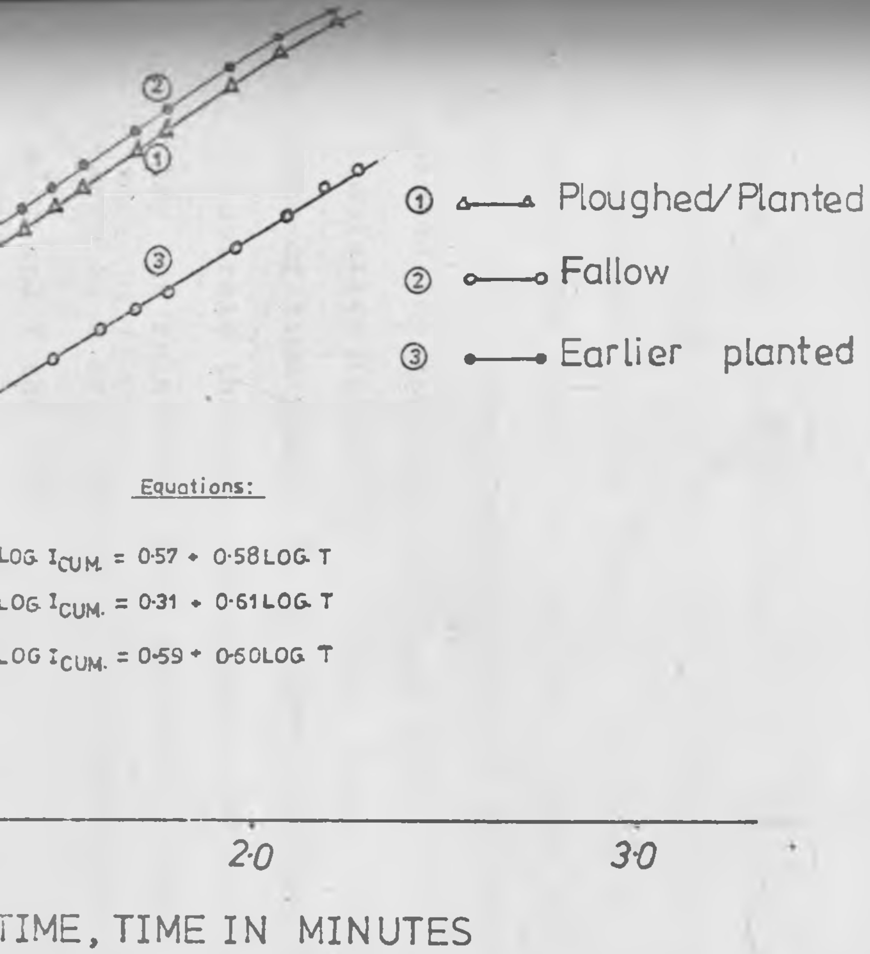

o——o Fallow
□——□ Ploughed/Recently Planted
△——△ Earlier Planted
CUMULATIVE INFILTRATION (CM.)
100
80
60
40
20
0
20
40
60
80
100
120
140
160
180
TIME IN MINUTES

Fig.7. Relationship between Logarithm of Cumulative Infiltration and Logarithm of time for three different surface conditions of the Mwea red soils.


2·0
1·0
0
LOG. I_CUM.' I_CUM. IN CENTIMETRES
1·0
LOG.
①
②
③



②
①
③
① Ploughed/Planted
② Fallow
③ Earlier planted
Equations:
LOG I_{CUM} = 0·57 + 0·58 LOG T
LOG $I_{CUM.}$ = 0·31 + 0·61 LOG T
LOG $I_{CUM.}$ = 0·59 + 0·60 LOG T
2·0
3·0
TIME, TIME IN MINUTES

after the first 20 minutes while the ploughed and/or recently planted had a varying infiltration with almost no water intake after about 3 hours. This lag in infiltration was possiblely due to the limiting plough layer, such that there was a considerable time lag as the wetting front passed the limiting layer. A plot of the logarithms of cumulative infiltration ($\mathrm{Log}_{10}\ I_{cum}$) against the logarithms of time ($\mathrm{Log}_{10}\ T$) is shown in Figure 7. These graphs illustrate that the infiltration rates of the red soils obey the relationship of Kostiakov (1932) of $I_{cum} = aT^{n}$ where a, n are characterising constants for a particular soil and T the time.

The volumetric water contents are shown in Appendix A1 for the two profiles of the Mwea red soils. Figures 1 and 2 illustrate the relationship between volumetric water content against suction in bars. The average amount of water held by the soil at 0.2 bar suction is about 41% while the average amount held by the soil at 15 bar suction is about 25%. This means that the average amount of moisture held by the soil between 0.2 and 15 bar suction is about 125 mm. for a metre depth of the red soil.

The bulk densities do not follow any regular pattern down the profile but are generally low. The second profile pit appears to have been compacted since the bulk densities of the top two horizons are higher than those of the lower three horizons.

Chemical analysis showed that the Mwea red soils have a soil reaction varying from strongly acidic to slightly acidic. The Mwea black soils have a reaction changing from moderately acidic to slightly alkaline with increasing depth. Most parts of the Mwea red soil are well supplied with bases but some few spots are low in potassium and calcium, particularly in the subsoil. The amounts of organic matter and nitrogen are rather low for both soils. The source of the phosphorus was found to be in weathering bedrock below the soil profile. The analysis of the bedrock for available phosphorus is shown on Table 3.

4.2. Water Use on the Kirogo Vegetable Scheme

A summary of the deep percolation efficiency which is the yardstick for seepage losses from the irrigated red soils of the Kirogo vegetable plot is shown in Appendix A8. The rainfall and evaporation during the period of study (January to December 1979) are shown on Appendices A9 and A10. The figures indicate that in four out of twelve months (January, June, July and August), excess water infiltrated the red soil profile in the Kirogo Vegetable Scheme. This means that some 340.8 mm of water infiltrated beyond the root zone and possibly ended up as seepage water in the poorly drained areas below the Kirogo village. The surface drained water comprises water that flows to the village for brick-

Table 3. Available phosphorus in weathering bedrock of the Mwea red soils

Sampling point and Depth (cm)	Available phosphorus (ppm)		
	Rep. I	Rep. II	Rep. III
1. 150-200	500	1155	1155
2. 100-200	308	1120	1060
3. 150-200	500	500	1250

Rep = Replicate

making and building purposes. Quite a good portion is left to flow into the poorly drained part below the village The amount of water that flowed off after brick-making and building activities was not possible to quantify during the study. The water did not flow along any regular channel and flow measurement devices could not be used to measure it.

Deep percolation efficiency increased with increasing rainfall (Fig. 8). This was because during the rainy periods no irrigation took place. As a result not much water was lost by deep percolation. Classified according to Hart et al. (1979) the deep percolation efficiency was lowest (poor) for most of the year (7 months). The efficiency was satisfactory for 5 months of the year (March, April, May, October and November).

In all the twelve months of 1979 more irrigation water was applied than was required in the vegetable scheme (Fig. 9). This excessive application of irrigation water contributed to the lowering of the deep percolation efficiency. During 1979 rainfall did not meet the requirement of evapotranspiration (appendix A11) for 9 months of the year. During 3 months (April, May, November) of the year there was excess of rainfall over evapotranspiration. This excess amounted to 411.5 mm. Of this quantity, the soil profile retained 200.1 mm. The rest 211.4 mm. contributed either to the deep percolation or to the surface

Fig.8. Relationship between Deep Percolation Efficiency(Ep) and Rainfall for different months of 1979 for Kirogo Vegetable Project, Mwea.

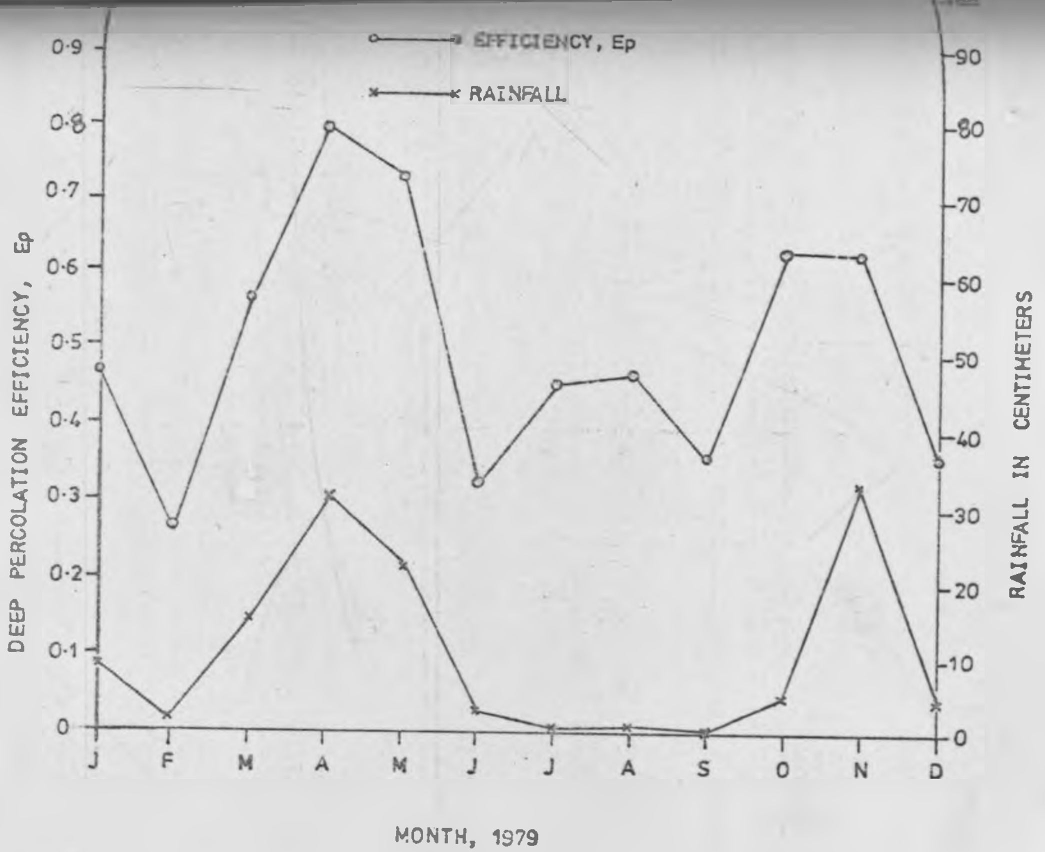
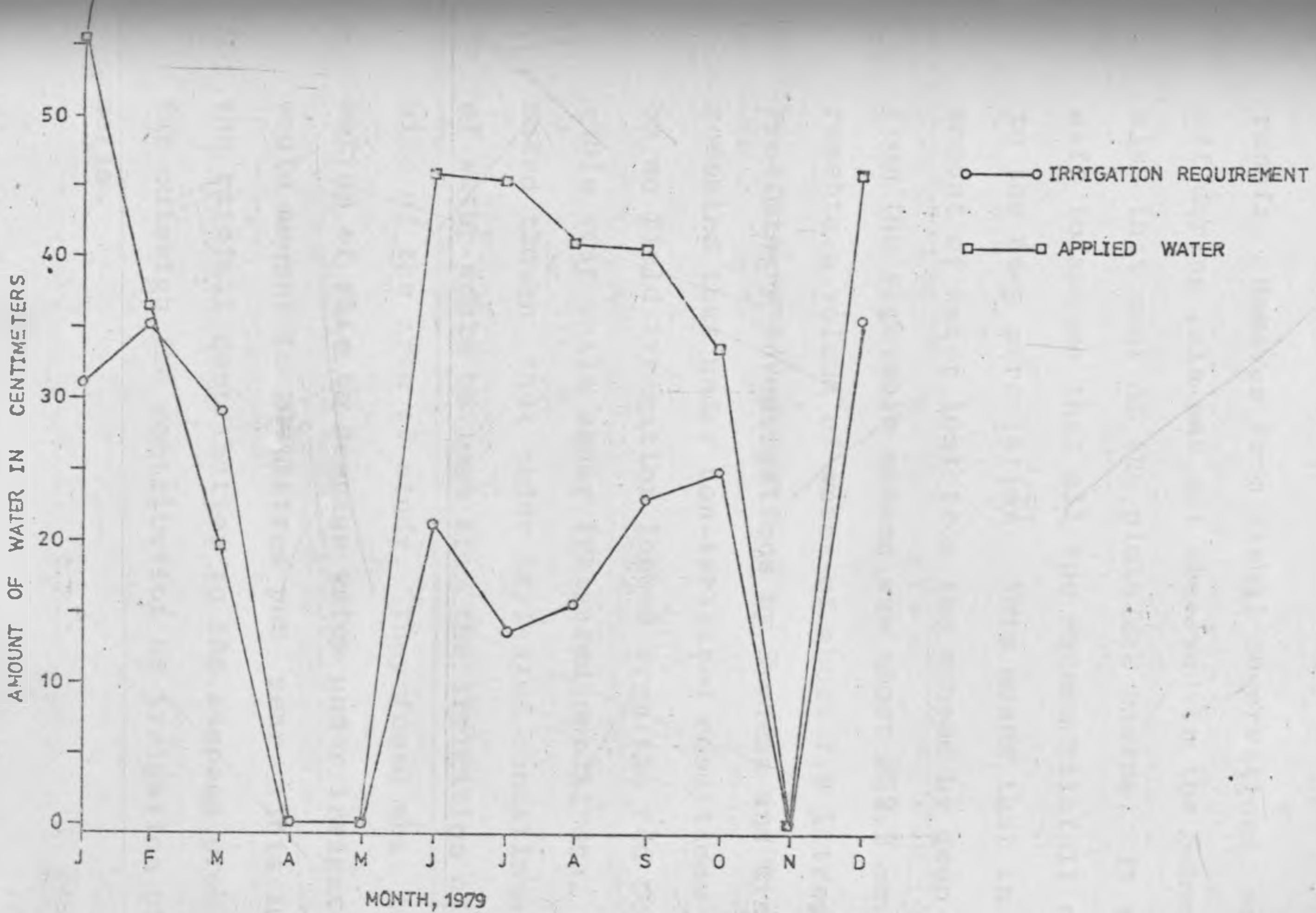

EFFICIENCY, Ep
RAINFALL
DEEP PERCOLATION EFFICIENCY, Ep
0
0·1
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
RAINFALL IN CENTIMETERS
0
10
20
30
40
50
60
70
80
90
J
F
M
A
M
J
J
A
S
O
N
D
MONTH, 1979

Fig.9. Relationship between Irrigation Requirement and applied water for Kirogo Vegetable Project during 1979.



AMOUNT OF WATER IN CENTIMETERS
50
40
30
20
10
0
J
F
M
A
M
J
J
A
S
O
N
D
MONTH, 1979
IRRIGATION REQUIREMENT
APPLIED WATER

runoff. However from visual observations, surface runoff during rain was not observed in the Scheme, noting also that most of the plots are basins. It was therefore safe to assume that all the excess rainfall contributed to the deep percolation. This means that in total, the amount of water lost from the scheme by deep percolation from the vegetable scheme was about 552.2 mm. This represents a volume of water of about 7.0 litres per year. Preliminary investigations by Smedema and Kinyali (1977) revealed that under non-irrigated conditions there would be no field irrigation losses from the red soils for the whole year while under irrigated conditions. They estimated though, that under irrigated conditions 40.0 litres of water would be lost from the irrigation of a plot the size of the area of study. They found that the contribution of rain to seepage water under irrigated condition would amount to 200 litres per year. This implied that the rainfall contribution to the seepage problem would far outweigh the contribution by irrigation of the red soils.

4.3. Canal Water Losses

Canal water measurements at two points at a distance of about 1.0 kilometre on the left branch canal of the Tebere main canal are shown in Appendix A12 and the statistical analysis is whown in Appendix A 13. The statistical analysis is shown in Appendix A 13. The statistical analysis using a t-test revealed significant differences in the flow between the upper and the lower points of measurement. Relation of canal water losses to groundwater fluctuations was not feasible because of the difficulty in controlling the canal water levels during the period of study.

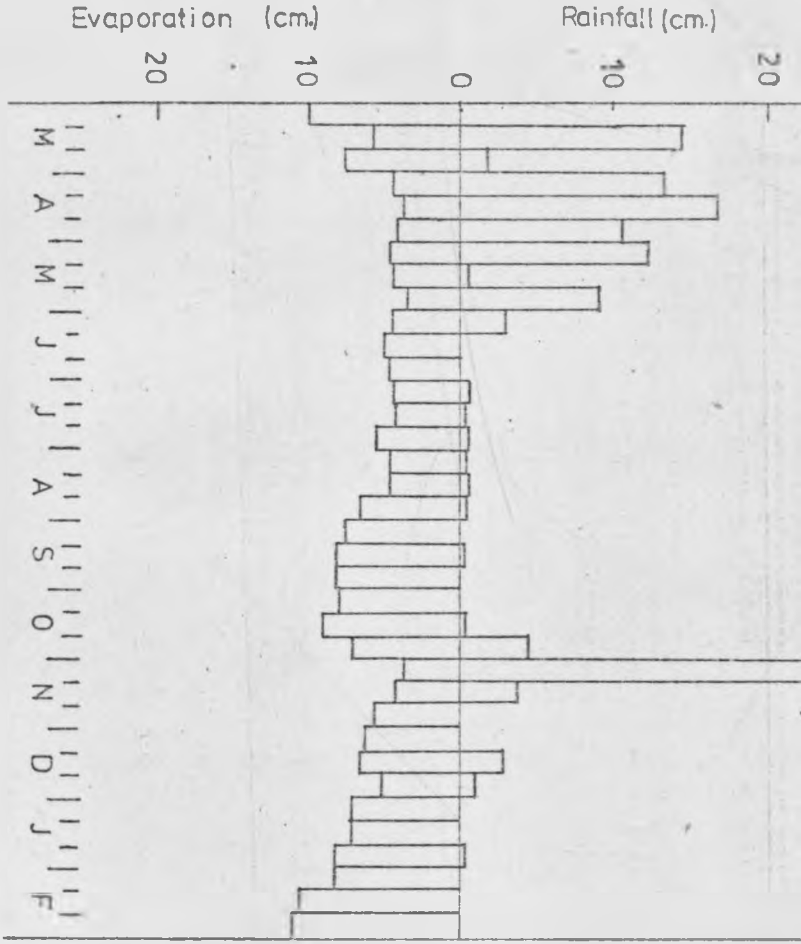
Smedema and Kinyali (1977) estimated that when the red soils were not irrigated, canal water losses amounted to 0.86 mm. per day or 413.9 mm in one year. With the red soils under irrigation they estimated an annual canal loss of about 501 mm. This study found that when only a small portion of the red soils is being irrigated in the Tebere Section, canal losses amounted to 4.5 mm/day or about 1642 mm per year. This is about four times the amount estimated by Smedema and Kinyali (1977). Work done by van Alphen et al. (1978), taking hydraulic conductivity measurements on the canal floor found that 900 mm. per year was lost from the canal as seepage, an amount only about half of what this study has found.

4.4. Groundwater Dynamics

The readings of groundwater levels for 10-day intervals are displayed in Appendix A 14. The results have been plotted in Fig. 10. Although the rains began in early March, the water level in piezometers only started to respond in early April reaching the peak rains (early April). The lag in response was most probably due to the water transmission properties of the soils in the study area. The saturated hydraulic conductivities of the soil have been shown in Appendix A4. The duration of the lag in response for each piezometer depends on the hydraulic conductivity of the soil at the point of installation (Richards, 1952).

Piezometers P2 and P8 were installed in the transition zone from the red (more permeable) clay loams to the black (less permeable) clays. This zone is characterised by the presence of an impermeable indurated murram volcanic tuff within only a few centimetres of the soil surface. This material has been observed to increase the confinement of the groundwater at the transition zone. Weak spots occur in the zone and water springs to the surface from such spots. It is in the transition zone that drainage problems start and water remains on the surface for most of the year. One other likely reason, therefore, for piezometers P2 and P8 showing little sharp response to rainfall was that whenever recharge was made to groundwater the water found way on to the surface to maintain equilibrium with the atmosphere. There was therefore little transmission of groundwater up the piezometer pipe. Piezometers P3 and P4 were installed in the red soil area. They showed a sharp response to rainfall.

Fig.10. Variation of piezometric head of groundwater with rainfall and evaporation(cm.) for one year(March 1979 to February 1980)


Evaporation (cm.)
Rainfall (cm.)
20
10
0
10
20
M
A
M
J
J
A
S
O
N
D
J
F

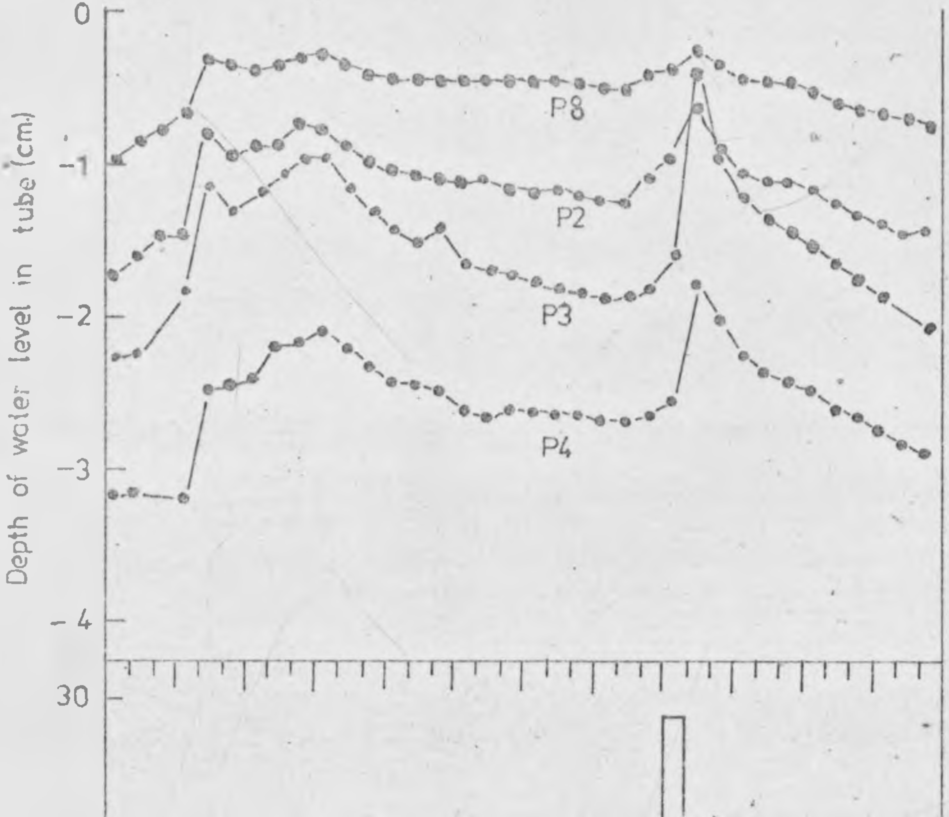
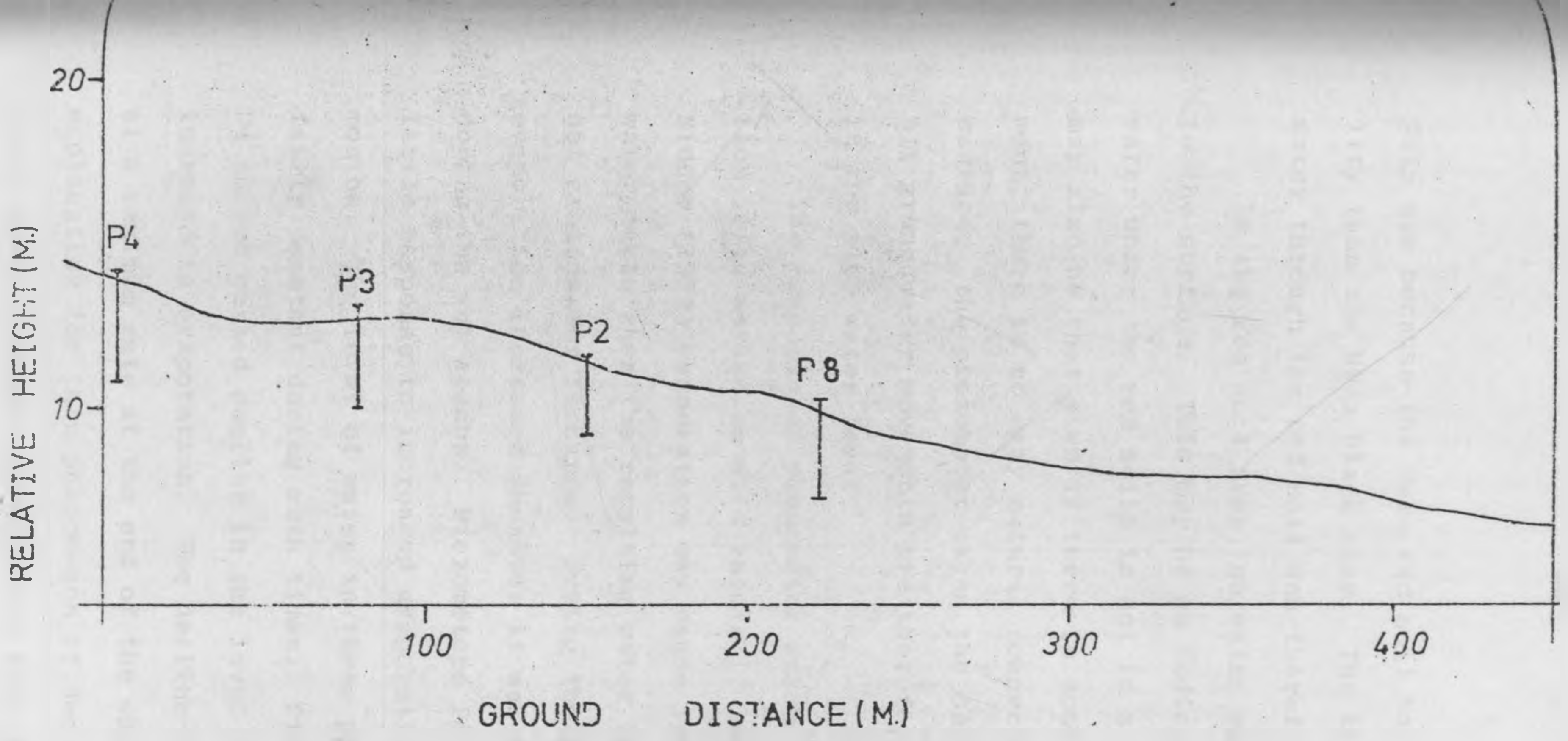

Depth of water level in tube (cm)
0
-1
-2
-3
- 4
30
P8
P2
P3
P4

Fig. II. Topography of piezometer line of installation(see Map 2).

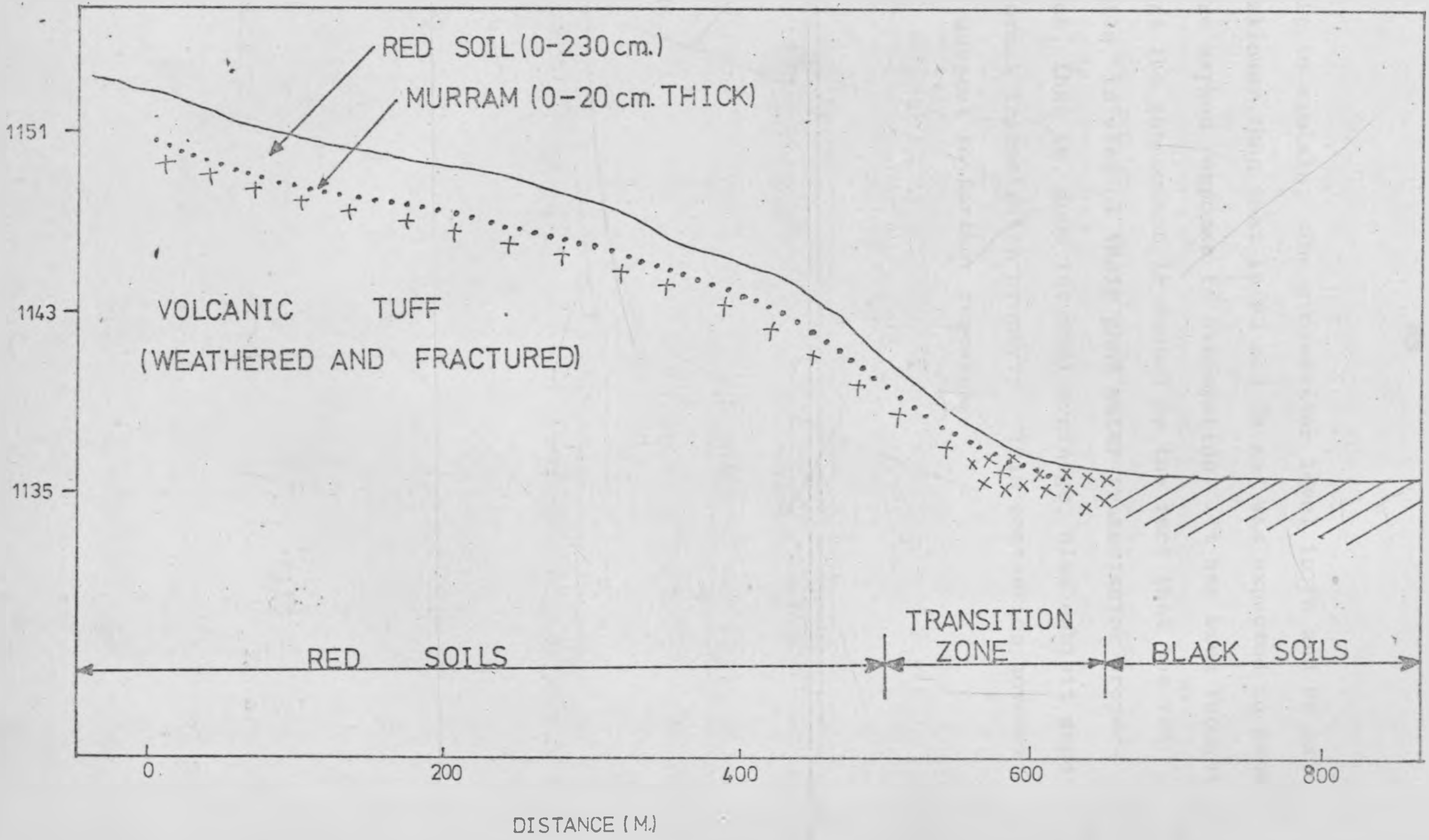

RELATIVE HEIGHT (M.)
20
10
P4
P3
P2
P8
100
200
300
400
GROUND DISTANCE (M.)

This was because the Mwea red soil has higher permeability than the Mwea black clay. The transmission of water through the red soil was therefore fast.

In the red soil area, no water was found to rise to the surface. This may be an indication that the groundwater under the red soils is not in a confined state. It may also be that even if there is some degree of confinement, there is no easy natural connection to the soil surface; the piezometer makes the only such connection. All groundwater movements are therefore only reflected in the pipe water level.

The response of piezometer water level to evaporation is not as marked as with rainfall. According to De Ridder (1974) evaporation may cause lowering of a shallow water table when the resulting water losses exceed the net groundwater recharge. During the period of study, evaporation increased whenever it was dry and decreased during the wet season. Piezometers P8 and P2 showed little response to increased evaporation during the dry months. The level of water in these pipes remained fairly constant during such times. Piezometers P3 and P4 showed marked decline in the level of water with increase in evaporation. The decline in water level was at a maximum rate at the end of the short rains. The explanation for this phenomenon of decline of water level with increased evaporation for P3 and P4 was diffi-

Fig. I2. Enlarged cross-section from A-B on Map 2 showing nature of soil profile from red to black soils of Mwea.


RED SOIL (0-230 cm.)
MURRAM (0-20 cm. THICK)
1151
1143
1135
VOLCANIC TUFF
(WEATHERED AND FRACTURED)
TRANSITION ZONE
RED SOILS
BLACK SOILS
0
200
400
600
800
DISTANCE (M.)

cult to explain. The groundwater level in P8 and P2 was shallower than that in P3 and P4 and was expected to show more marked response to evaporation. It has been thought that the phenomenon is caused by the fact that the red soils, in view of their good water transmission properties, that is, good internal drainage, also exhibit good thermal transmission property. This contention,however is subject to further research.

5. SUMMARY AND CONCLUSIONS

From a study of the drainage problems around the village of Kirogo in the Tebere Section of the Mwea Irrigation Scheme conducted in 1979 and part of 1980, the following conclusions may be made:

(1) The mature profile of the Mwea red soil contains adequate nutrients available for crop growth. The profile had saturated hydraulic conductivity which was moderately rapid in the top soil, reducing to very slow in the lower subsoil. The Mwea black clay soil had low hydraulic conductivity throughout the profile. The planted red soil plots had higher basic infiltration rates than both the fallow and the recently ploughed/planted sites. The moisture held between 0.2 and 15 bar suction values amounted to 125 mm per metre of the red soil profile.

(2) The combined effect of rainfall and excess irrigation water from 11.1 hectares behind Kirogo village contributed only 7.0 litres during the year 1979 towards the seepage flow which believably ended in the poorly drained area below Kirogo village. Of this amount rainfall accounted for over 75%.

Rainfall was therefore a major cause of the drainage problems in the study area.

(3) There were detectable losses in canal water during 1979. These losses amounted to 1642 mm., using an 'OTT' current meter to measure losses between two points at a distance of 1 km. apart on the left branch canal of the Tebere main canal. This is equivalent to a loss rate of 2.6 litres per second per kilometre length of canal passing over the red soils.

(4) Rainfall had a marked influence on the dynamics of groundwater below the poorly drained area around Kirogo village. Rainfall contributed both to the groundwater recharge and to the surface water reservoir and thus affected the drainage of the area significantly.

(5) Controlled irrigation of the red soils may pose no danger of agravating the drainage problems currently anticipated when the red soils are put under irrigation. Canal water losses seem to be biggest problem to be solved in the Tebere Section of the Mwea Scheme.

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APPENDICES

APPENDIX A1 – Moisture content (volume %) at different suctions (Bars) and Bulk Density

Profile Number	Depth in cm.	Moisture content at Suction:							Bulk Density gm. cc^{-1}
		SAT.	0.1BAR	0.2 BAR	0.5 BAR	1.0 BAR	5.0BAR	15.0 BAR	
1	0-25	57.1	39.9	36.8	34.3	32.5	26.4	24.5	1.10
	25-48	54.4	45.0	42.0	40.3	38.9	32.1	29.8	1.25
	48-106	55.1	46.2	43.2	41.2	39.7	33.4	30.9	1.24
	106-150	55.4	46.6	43.5	41.1	39.9	32.4	30.1	1.23
2	0-25	55.5	46.1	43.5	41.2	39.7	32.5	30.4	1.33
	25-48	55.3	42.9	40.9	38.7	37.3	31.2	30.8	1.23
	48-125	58.3	44.2	40.0	37.9	36.1	29.7	28.0	1.13
	125-195	58.3	46.8	43.3	40.4	38.4	31.3	30.9	1.16
	195-239	58.9	47.3	43.1	39.6	37.8	29.9	29.2	1.15

APPENDIX A2. Water Released (mm) at different suctions (bars)

Profile Number	Depth in cm.	Water released (mm.) at suctions:					
		0.1 BAR	0.2 BAR	0.5 BAR	1.0 BAR	5.0 BAR	15.0 BAR
1	0-25	17.2	20.3	22.8	24.6	30.7	32.6
	25-48	9.4	12.4	14.2	14.6	22.3	24.6
	48-106	9.0	11.9	13.9	15.4	21.7	24.2
	106-150	8.0	11.9	14.3	15.5	23.0	25.3
2	0-25	9.4	12.0	14.3	15.8	23.0	25.1
	25-48	12.4	14.4	16.6	18.0	24.1	24.5
	48-125	14.4	18.5	20.6	22.4	28.8	30.5
	125-195	11.4	15.0	17.8	19.8	27.0	27.4
	195-239	11.7	15.0	19.3	21.1	29.0	29.7

APPENDIX A3: Basic Infiltration Rates of the Mwea Red Soils

Time in minutes	Infiltration Rates* (cm.hr^{-1})			Cumulative Infiltration* (cm.)		
	PLOT A	PLOT B	PLOT C	PLOT A	PLOT B	PLOT C
5	68.1	162.5	181.4	5.6	11.7	11.8
10	39.3	42.3	71.1	8.8	15.2	17.7
15	27.2	28.7	37.8	11.0	17.6	20.8
20	19.7	31.8	37.8	12.6	20.2	23.9
30	21.2	31.3	33.3	16.1	25.3	29.8
40	19.7	31.8	34.8	19.3	30.8	35.6
50	14.4	27.2	25.7	21.7	34.7	40.6
60	17.4	30.2	21.2	24.6	38.8	44.7
90	13.9	39.3	27.2	31.4	54.8	57.6
120	15.4	15.1	22.7	39.0	63.1	69.0
150	12.6	--	--	45.2	68.0	--
180	13.9	5.7	--	52.0	68.7	--

Plot A = Non- ploughed non-used sites; Plot B = ploughed/recently planted sites:
Plot C = earlier planted sites; * The given values are averages for 14 sites per plot.

APPENDIX A4. Saturated hydraulic conductivity (K-value) cm.hr^{-1} and classes for the Mwea soils.

Soil property	Direction	Red Soil Horizon (Pit 1)				Red Soil Horizon (Pit 2)					Black Soil Horizon	
		0-25 cm.	25-48 cm.	48-106 cm.	106-150+ cm.	0-25 cm.	25-48 cm.	48-125 cm.	125-195 cm.	195-239+ cm.	0-28 cm.	28 100 cm.
K-value	Vertical	6.20	13.04	0.43	0.33	8.57	1.83	0.34	0.88	1.23	3.04	0.01
	horizontal	2.74	5.02	0.51	0.19	9.93	2.42	0.62	0.32	1.92	0.59	0.01
K-class	vertical	4	5	1	1	4	2	1	2	2	3	0
	horizontal	3	3	1	0	4	3	2	1	2	2	0

Hydraulic conductivity classes (k-class): 0 = very slow (<0.125 cm.hr.$^{-1}$); 1 = slow (0.125-0.5 cm.hr.$^{-1}$); 2 = moderately slow (0.5 - 2.0 cm.hr.$^{-1}$); 3 = moderate (2.0-6.25 cm.hr.$^{-1}$); 4 = moderately rapid (6.25-12.5 cm.hr.$^{-1}$); 5 = rapid (12.5-25.0 cm.hr.$^{-1}$); 6 = rapid (> 25.0 cm.hr.$^{-1}$).

APPENDIX A5. Description of Mwea Red Soil Profile

Pit 1.

Location: South-eastern part of the vegetable scheme. Newly opened pit.

Slope: 1%, flat to almost flat middle slope to the south east. Linear and single slope. Macro-relief is flat to very gently undulating. Micro-relief: ridges are made for furrow irrigation; ridges roughly 20 cm. high.

Parent material: Olivine basalt/volcanic tuff.

Vegetation/Land Use: Vegetables, tree crops growing under irrigation. Rainfed cotton growing near the vegetable scheme. Human influence include ploughing, irrigation, application of farm yard manure and ridging.

Surface Runoff: Very slow.

Soil fauna: Safari ants/termites.

Effective soil depth: Very deep (150+ cm.)

Root distribution: Maximum root density at 0-47 cm. Roots found up to 150 cm.

0-25 cm. Dark reddish brown (5YR2.5/2 moist); clay; granular, fine to medium moderate

	structure; very friable when moist; many fine to very fine pores; abundant roots; gradual and smooth boundary to:
25-48 cm.	Dark reddish brown (5YR3/2 moist); clay; granular and sub-angular blocky, fine to medium moderate structure; friable when moist; many very fine to fine pores; patchy, thin clay cutans; abundant roots; gradual and wavy transition to:
48-105 cm.	Dark reddish brown (5 YR 3/2-3 moist); clay; moderate, medium sub-angular blocky structure; friable when moist- many very fine to fine pores; thin, broken clay cutans, regular roots; gradual and wavy transition to:
105-150+ cm.	Dark reddish brown (5 YR3/2-3 moist); clay; few stones; moderate, medium to coarse sub-angular blocky structure; friable when moist; many very fine pores; thin patchy clay cutans; few roots; weathering bedrock after 150+ cm.; soil moist at the time of description/sampling.

APPENDIX A6. Description of Mwea Red Soil Profile

Pit 2

Location: Southern part of the vegetable scheme about 50 m. north of Kirogo village. Old pit reopened.

Slope: 1%, flat land; surrounding land form gently sloping to the south.

Parent material: Olivine basalt/volcanic tuff.

Vegetation/Land Use: Vegetable and tree crops grown under irrigation. Maize, beans and cotton growing under rainfed conditions.

Surface runoff: Very slow.

Effective soil depth: Extremely deep (239 cm+); well drained.

Root Distribution: Maximum root density at 0-42 cm. Roots upto 239 cm.

0-25 cm. Dark reddish brown (5 YR 3/2 moist); clay; granular fine to medium moderate structure; very friable when moist; many micro- and bio- pores; thin. patchy clay cutans; abundant fine to medium roots; gradual and smooth boundary to:

25 - 48 cm.	Dark reddish brown (5 YR 3/3 moist); clay; granular fine to medium moderate structure; very friable when moist; many micro- and bio- pores; thin, common clay cutans in lower part of horizon; abundant very fine to fine roots; gradual and wavy boundary to:
48-125 cm.	Dark reddish brown (5 YR 3/3 moist); clay: moderate medium to coarse sub-angular blocky structure; friable when moist; many micro- and bio- pores; thin common clay cutans; many very fine to fine roots; gradual and smooth boundary to:
125-195 cm.	Dark reddish brown (5 YR 3/3 moist); clay; moderate, medium to coarse sub-angular blocky structure; friable when moist; few thin clay cutans; few micro- and bio- pores; few very fine to fine roots; gradual smooth boundary to:
195-239+ cm	Dark reddish brown (5 YR 3/3 moist); clay; stony in lower part; moderate medium to coarse sub-angular blocky structure; friable when moist; few, thin clay cutans; few micro- and bio-

pores; few very fine to fine roots; gradual and smooth boundary; weathering bedrock after 239 cm; soil moist rill weathering bedrock at time of description/sampling.

APPENDIX A7.1. Classification of Basic Infiltration Rates (after Rickard and Cossens, 1965)

Class	Intake Designation	Basic Infiltration rate (mm.hr.$^{-1}$)
0	very low	< 2.5
I	low	25 - 15
II	medium	15 - 28
III	high	28 - 53
IV	very high	> 53

APPENDIX A7.2. Classification of Saturated Hydraulic Conductivity (after O'Neal, 1952)

Class	Intake Designation	Hydraulic Conductivity ($cm.hr.^{-1}$)
0	very slow	< 0.125
I	slow	0.25 - 0.5
II	moderately slow	0.5 - 2.0
III	moderate	2.0 - 6.25
IV	moderately rapid	6.25 - 12.5
V	rapid	12.5 - 25.0
VI	very rapid	> 25.0

APPENDIX A8. Ten-day deep percolation efficiency calculation for January to December 1979 for Kirogo Vegetable Scheme

Period	Irrigation Requirement	Applied Water	Surface Drainage	Evapotranspiration	Deep percolation Efficiency
1979	(mm.)	(mm.)	(mm.)	(mm.)	Ep
Jan. 1.	126.4	201.2	81.2	50.6	0.44
2.	96.3	261.3	100.0	49.0	0.43
3.	89.1	94.2	50 6	51.2	0.55
Feb. 1.	112.5	120.6	45.2	50.1	0.29
2.	142.3	159.3	101.0	55.0	0.25
3.	98.2	102.1	60.8	49.8	0.26
Mar. 1.	100.7	100.0	30.6	61.1	0.18
2.	102.0	0.0	0.o	58.7	0.89
3.	86.2	90.0	24.6	57.0	0.64
Apr. 1	0.0	0.0	0.0	52.9	0.72
2.	0.0	0.0	0.0	49.1	0.79
3.	0.0	0.0	0.0	49.2	0.86
May 1.	0.0	0.0	0.0	49.9	0.80
2.	0.0	0.0	0.0	47.0	0.68
3.	0.0	80.0	20.1	44.9	0.70
Jun. 1	92.6	126.0	30.2	42.4	0.53
2.	39.3	142.6	80.9	44.5	0.26
3.	86.3	196.2	82.7	37.4	0.21
Jul. 1.	56.4	202.6	90.6	37.0	0.29
2,	42.7	136.9	89.4	37.7	0.46
3.	71.8	124.7	84.3	44.2	0.62
Aug. 1.	90.1	200.0	100.3	40.0	0.42
2.	46.7	136.3	93.4	41.0	0.51
3	20.2	87.6	66.4	57.3	0.47
Sept.1.	120.6	127.8	92.8	50.7	0.36
2.	43.7	120.1	100.2	56.1	0.31
3.	91.6	115.6	87.9	57.4	0.42
Oct. 1.	62.7	126.4	62.4	57.8	0.61
2.	120.4	156.6	83.8	59.5	0.52
3.	70.2	90.7	42.1	59.8	0.75
Nov. 1.	4.6	0.0	0.0	44.3	0.86
2.	10.2	0.0	0.0	46.4	0.43
3.	22.6	0.0	0.0	54.5	0.60
Dec. 1.	142.5	186.2	120.6	52.8	0.40
2.	92.6	100.4	60.2	50.1	0.32
3.	126.4	186.8	101.6	48.5	0.37
Total	2370.5	3736.4	1703.0	1794.9	

APPENDIX A9. Rainfall in millimeters for Kirogo Vegetable Scheme, 1979.

	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.
1	NIL	1.8	NIL	0.3	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
2	"	1.3	"	NIL	43.0	21.5	"	2.1	"	"	"	"
3	"	11.0	"	"	0.7	3.0	"	NIL	"	"	59.7	"
4	"	NIL	"	0.1	NIL	NIL	"	"	"	"	4.6	"
5	"	2.0	"	17.0	28.0	2.8	"	"	"	"	50.5	"
6	"	NIL	"	22.0	NIL	NIL	"	"	"	"	60.0	"
7	11.6	"	"	NIL	17.0	"	1.6	"	"	"	0.5	"
8	6.4	0.6	"	2.5	17.2	"	2.0	"	"	"	51.0	"
9	0.5	NIL	"	25.0	18.0	0.8	NIL	"	"	"	55.0	"
10.	NIL	NIL	NIL	67.2	NIL	NIL	NIL	0.4	NIL	NIL	8.5	NIL
11.	0.1	3.2	NIL	99.6	3.3	NIL	NIL	NIL	0.5	NIL	26.0	NIL
12.	NIL	NIL	0.1	44.6	NIL	"	"	"	NIL	"	10.5	"
13	3.2	"	19.0	NIL	0.6	"	"	"	2.0	"	NIL	"
14	NIL	"	NIL	2.3	NIL	"	"	2.5	NIL	"	"	"
15	"	"	20.0	13.5	"	"	"	NIL	"	"	"	"
16	6.2	"	NIL	0.1	"	"	0.6	0.6	"	"	"	"
17	NIL	"	17.0	NIL	"	"	NIL	NIL	"	"	"	"
18	"	"	65.0	"	"	"	"	"	"	3.1	"	16.5
19	3.5	"	13.3	"	"	"	"	"	"	NIL	"	5.0
20	NIL	NIL	11.0	7.2	NIL	NIL	0.5	NIL	NIL	NIL	NIL	9.0
21	2.0	NIL	1.2	NIL	0.1	NIL	NIL	NIL	NIL	NIL	NIL	NIL
22	4.5	"	NIL	0.5	NIL	"	"	"	"	17.8	"	"
23	3.3	"	"	NIL	2.7	"	"	"	"	12.5	"	"
24	NIL	"	"	6.7	47.8	"	0.6	"	"	NIL	"	2.1
25	4.1	"	"	60.7	6.7	"	NIL	"	"	15.0	"	0.5
26	8.9	"	0.5	11.8	6.5	"	2.4	"	"	NIL	"	4.5
27	16	"	NIL	0.2	14.4	"	NIL	2.5	"	"	"	NIL
28	NIL	NIL	"	2.6	10.6	"	"	NIL	"	"	"	"
29	"	"	"	7.6	0.2	"	"	"	"	"	"	3.8
30	34.0	"	"	14.6	0.5	NIL	"	"	"	"	"	NIL
31	1.4		NIL				NIL	NIL		NIL		NIL

APPENDIX A10. Evaporation in millimetres for Kirogo Vegetable Scheme, 1979.

	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.
1	6.6	2.9	14.7	5.0	5.0	2.3	3.8	1.5	4.7	8.5	7.2	6.5
2	3.5	2.9	8.6	5.5	3.1	2.4	4.0	4.5	6.0	9.3	6.3	5.5
3	6.9	3.0	13.6	5.2	3.6	5.0	2.0	6.0	7.5	7.6	3.4	5.5
4	5.8	3.8	12.4	5.3	3.8	4.0	4.5	7.0	11.5	6.5	3.8	5.7
5	5.9	5.1	11.5	5.1	8.0	4.0	5.9	5.8	6.5	7.0	1.0	7.0
6	4.0	5.4	9.9	3.4	5.2	4.4	2.8	4.7	9.5	7.5	3.0	5.5
7	2.8	4.5	9.5	3.1	4.1	6.4	3.4	2.1	7.5	7.8	2.1	5.8
8	3.6	6.0	8.4	3.7	3.5	5.8	4.2	5.0	9.0	8.7	4.4	6.9
9	4.0	5.5	6.7	4.0	5.0	6.0	6.2	4.8	6.5	9.9	3.5	6.8
10.	4.8	5.8	6.0	3.5	4.4	5.2	7.0	3.0	6.0	7.8	1.0	6.8
11	4.4	5.7	6.7	2.5	4.0	4.4	6.3	3.2	6.5	10.6	2.3	4.9
12	5.6	5.6	6.8	2.0	4.2	4.7	5.3	6.0	6.5	11.5	2.6	6.5
13	5.0	5.3	6.2	3.3	3.9	5.8	3.0	3.4	6.5	8.5	2.0	9.9
14	5.7	5.9	6.8	3.5	4.2	5.2	1.9	2.0	7.5	7.6	4.5	7.5
15	5.0	5.0	5.5	4.2	4.0	4.5	2.5	2.5	8.0	8.0	3.9	6.8
16	2.3	6.0	4.6	4.9	4.8	4.7	2.9	3.9	9.5	7.5	4.3	7.5
17	2.5	6.0	6.1	5.1	4.5	5.5	5.9	5.0	9.7	7.5	4.5	3.5
18	4.5	6.0	5.0	4.7	4.9	5.0	5.8	7.0	9.2	8.7	4.8	4.5
19	4.8	4.8	3.9	4.5	5.0	4.9	5.0	5.9	7.9	8.4	6.3	3.8
20	5.1	7.0	5.6	2.8	4.0	4.7	4.5	6.5	8.6	10.8	4.5	9.0
21	3.1	7.0	7.2	5.0	3.3	5.8	6.3	6.4	9.6	10.0	5.5	2.5
22	3.5	6.1	7.9	4.0	3.4	5.2	4.2	7.6	8.7	5.4	5.3	4.0
23	4.5	6.4	7.1	4.1	1.0	5.5	8.0	5.4	7.5	5.5	5.5	6.0
24	5.8	7.0	6.7	4.4	2.3	3.4	4.3	5.3	8.5	4.5	6.0	3.0
25	2.9	7.1	7.9	2.7	2.4	4.5	3.9	4.6	9.3	4.0	5.0	4.1
26	2.9	8.1	5.6	2.5	1.5	4.2	2.0	5.2	5.0	4.0	5.0	4.9
27	4.5	8.0	6.0	3.0	1.0	3.0	3.0	6.5	6,9	4.7	5.5	5.5
28	4.5	7.4	7.0	4.4	4.4	8.6	4.0	7.2	7.8	6,8	6.0	5.1
29	3.7		6.8	3.2	3.7	3.0	6.0	7.5	8.2	6.4	6.0	4.8
30	3.1		6.5	6.5	5.0	4.0	6.0	6.8	9.0	10.0	5.5	5.0
31	2.2		6.0		8.4		7.0	3.8		7.8		6.2

APPENDIX A 11. Monthly water application summary for the Kirogo Vegetable Scheme, 1979.

Month 1979	Irrigation Requirement (mm.)	Applied Water (mm.)	Surface Drainage (mm.)	Infiltrated Water (mm.)	Excess (+) or Deficit (-) (mm.)
Jan.	311.8	556.7	231.8	324.9	+ 13.1
Feb.	353.0	382.0	207.0	175.0	- 178.0
Mar.	288.9	190.0	55.2	134.8	- 154.1
Apr.	0.0	0.0	0.0	0.0	0.0
May	0.0	0.0	0.0	0.0	0.0
Jun.	218.2	464.8	20.1	444.7	+ 226.5
Jul.	170.0	463.3	193.8	269.5	+ 98.6
Aug.	157.0	423.9	264.3	159.6	+ 2.6
Sept.	255.9	408.5	260.1	148.4	- 107.5
Oct.	253.3	373.7	188.3	185.4	- 67.9
Nov.	0.0	0.0	0.0	0.0	0.0
Dec.	361.5	473.4	282.4	191.0	- 170.5

APPENDIX A12. Canal water measurements on left branch of Tebere main canal.

Experiment Number	Mean volume flow at different points (m^3 sec^{-1})		Difference in mean volume flow (m^3sec^{-1})
	Upper	Lower	
1	0.7729	0.7513	0.0216
2	0.7816	0.7624	0.0192
3	0.8933	0.7721	0.1212
4	0.7719	0.7539	0.0180
5	0.8249	0.8052	0.0197
6	0.8757	0.8126	0.0631
7	0.9388	0.8046	0.1342
8	0.9307	0.8187	0.1120
9	0.9503	0.9264	0.0239
10	1.0214	0.9193	0.1021
11	0.9751	0.9390	0.0361
12	0.7965	0.7676	0.0289
13	1.0493	0.9921	0.0572
14	1.0488	1.0199	0.0621
15	0.9904	0.9567	0.0337
16	0.9763	0.9302	0.0461
17	1.0154	0.8936	0.1228
18	1.0293	0.9192	0.1101
19	0.9343	0.8672	0.0671
20	0.8956	0.8526	0.0430
21	0.8380	0.8088	0.0292
22	0.8630	0.8275	0.0355
23	0.8765	0.8472	0.0293
24	0.9042	0.8826	0.0216
25	0.8528	0.8247	0.0281
26	0.8951	0.8762	0.0189
27	0.8863	0.7627	0.1236
28	0.9214	0.8212	0.1002
29	0.9311	0.9129	0.0182
30	0.8129	0.7933	0.0196
31	0.8451	0.8029	0.0422
32	0.7801	0.7622	0.0179
33	0.8480	0.8211	0.0261
34	0.8335	0.8021	0.0314
35	0.9353	0.8000	0.1353
36	0.8239	0.8045	0.0194
37	0.8289	0.8026	0.0263
38	0.8310	0.8032	0.0278
39	0.8661	0.8462	0,0199
40	0.9640	0.8613	0.1027
41	0.8869	0.8398	0.0471
42	0.9526	0.9247	0.0279
43	0.9625	0.9367	0.0258
44	0.9426	0.9230	0.0196
45	0.9395	0.9120	0.0275
46	0.8947	0.8686	0.0261
47	0.8633	0.8329	0.0309
48	0.9303	0.7963	0.1340
49	0.7190	0.6823	0.0367
50	0.9034	0.7821	0.1213

APPENDIX A13. Statistical Analysis of the Canal Water Flow at two points of Left Branch Canal Tebere

Calculation of the means (n = 50)

$\Sigma x_i = 44.8050$: $\Sigma x_2 = 42..2262$

$\bar{x}_1 = 0.8961$: $\bar{x}_2 = 0.8445$

$(\Sigma x_i)^{2}/n = 40.1489$: $(\Sigma x_2)^{2}/n = 35.6610$

$\Sigma x_1^2 = 40.4358$: $\Sigma x_2^2 = 35.8990$

$\Sigma x_1^2 - (\Sigma x_1)^{2}/n = 0.2869$: $\Sigma x_2^2 - (\Sigma x_2)^{2}/n = 0.2380$

Calculation of the variances $S_i^{\,2}$

$$Si^2 = (\Sigma x^2 - (\Sigma x)^{2}/n) / (n-1)$$

$S_1^2 = 0.2860/49$: $S_2^2 = 0.2380/49$

Calculation of F-ratio; $F_c = S_1^2/S_2^2$

$F_c = 0.0059/0.0049$

$F_c = 1.2147$

$F_{0.05(49,49)} = 1.68$

$F_{0.01(49,49)} = 2.10$

$F_{\binom{0.05}{0.01}(49,49)} > F_c$

The variances S_1^2 and S_2^2 are reasonably similar.

Calculation of pooled variance S^2

$$S^2 = S_1^2 + S_2^2$$

$$S_2^2 = 0.0059 + 0.0049$$

$$S_2^2 = 0.0108$$

Calculation of variance of $\bar{\bar{X}} - \bar{X}_2$

$$\text{Var}\ (\bar{X} - \bar{X}_2) = 2S^2/n$$

Calculation of the standard error of the difference, SED

$$\text{SED} = (2S^2/_n)^{\frac{1}{2}}$$

$$\text{SED} = ((2 \times 0.0108)/50)^{\frac{1}{2}}$$

$$\text{SED} = 0.0208$$

Calculation of the t-value, t_c.

$$t_c = (\bar{X}_1 - \bar{X}_2)/\text{SED}$$

$$t_c = 2.4826$$

$$t_{(0.01;\ 98)} = 2.633$$

$$t_{(0.05;\ 98)} = 1.989$$

$$t_{(0.01,\ 98)} = 2.633 > t_c$$

We reject the null hypothesis of equality of mean flows at 1% level of significance. There is therefore detectable water losses between the two points of measurements on the left branch canal of the Tebere main canal.

APPENDIX A14. Ten-day piezometer readings in metres (with standard errors) for the period March 1979 to February 1980

Period		Piezometer Number				Standard Errors, SE$_{\bar{x}}$			
		P8	P2	P3	P4	P8	P2	P3	P4
Mar.	1.	0.79	1.73	2.27	3.16	0.01	0.01	0.02	0.01
	2.	0.86	1.61	2.25	3.16	0.07	0.09	0.00	0.00
	3	0.78	1.48	2.27	3.18	0.02	0.03	0.00	0.00
Apr.	1	0.67	1.46	1.84	3.18	0.06	0.12	0.00	0.00
	2	0.32	0.80	1.13	2.49	0.02	0.07	0.04	0.08
	3	0.37	0.95	1.31	2.46	0.02	0.04	0.02	0.01
May	1	0.39	0.88	1.18	2.40	0.02	0.05	0.07	0.03
	2	0.37	0.87	1.08	2.18	0.01	0.02	0.03	0.01
	3	0.31	0.75	0.97	2.18	0.02	0.05	0.06	0.03
Jun.	1	0.29	0.77	0.98	2.08	0.00	0.02	0.02	0.01
	2	0.36	0.89	1.17	2.20	0.01	0.01	0.02	0.01
	3	0.43	1.00	1.33	2.34	0.00	0.01	0.02	0.02
July	1	0.45	1.05	1.43	2.42	0.00	0.01	0.01	0.01
	2	0.45	0.07	1.52	2.44	0.00	0.00	0.01	0.00
	3	0.45	1.11	1.61	2.49	0.00	0.00	0.01	0.01
Aug.	1	0.45	1.12	1.66	2.59	0.00	0.00	0.01	0.01
	2	0.45	1.11	1.69	2.66	0.01	0.01	0.00	0.02
	3	0.45	1.14	1.73	2.58	0.00	0.01	0.01	0.02
Sept.	1	0.45	1.17	1.78	2.61	0.00	0.00	0.00	0.01
	2	0.44	1.16	1.82	2.62	0.00	0.00	0.01	0.00
	3	0.46	1.19	1.85	2.64	0.00	0.00	0.00	0.00
Oct.	1	0.48	1.22	1.87	2.66	0.00	0.00	0.00	0.00
	2	0.50	1.25	1.87	2.68	0.00	0.00	0.01	0.01
	3	0.41	1.06	1.80	2.64	0.01	0.03	0.00	0.00
Nov.	1	0.38	0.93	1.61	2.53	0.03	0.08	0.11	0.03
	2	0.25	0.61	0.40	1.77	0.02	0.03	0.04	0.04
	3	0.35	0.89	0.95	2.01	0.01	0.02	0.04	0.03
Dec.	1	0.44	1.04	1.21	2.24	0.01	0.01	0.02	0.01
	2	0.45	1.10	1.35	2.36	0.02	0.01	0.01	0.01
	3	0.45	1.07	1.44	2.42	0.01	0.01	0.01	0.01
Jan.	1	0.53	1.15	1.52	2.48	0.01	0.01	0.01	0.01
	2	0.58	1.25	1.66	2.59	0.00	0.01	0.02	0.01
	3	0.62	1.31	1.75	2.65	0.00	0.00	0.01	0.00
Feb.	1	0.64	1.38	1.87	2.75	0.01	0.01	0.01	0.01
	2	0.69	1.44	1.98	2.82	0.00	0.00	0.02	0.01
	3	0.72	1.42	2.06	2.87	0.00	0.04	0.01	0.00

APPENDIX A15. U.S.D.A. Triangle for Texture Classification.