DETERMINATION OF SOIL MOISTURE CONTENT AND RELATED PARAMETERS FOR SUSTAINABLE AGRICULTURE IN ZARIA.

BY

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DECLARATION

I declare that the work in the dissertation entitled '**Determination of Soil Moisture Content and Related Parameters for Sustainable Agriculture in Zaria.**' has been performed by me in the Department of Physics under the supervision of Dr L.A. Dim.

The information derived from literature has been duly acknowledged in the text and a list of reference provided. No part of this dissertation was previously presented for another degree or diploma at any university.

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CERTIFICATION

This dissertation entitled "**DETERMINATION OF SOIL MOISTURE CONTENT AND RELATED PARAMETERS FOR SUSTAINABLE AGRICULTURE IN ZARIA.**" by Baba-Kutigi, Adamu Nchama meets the regulations governing the award of Doctor of Philpsophy of Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

The work is dedicated to my family for their encouragement, especially the little one's that always want Baba to be by their sides.

ABSTRACT

The capacitance probe (*Diviner 2000*), an electromagnetic based soil water content measuring instrument incorporates soil into an oscillator circuit to measure frequency. The International Atomic Energy Agency, IAEA donated a capacitance probe to the Centre for Energy Research and Training, Ahmadu Bello University, Zaria, Nigeria. The *Diviner 2000* had been used to determine soil water content and for planning irrigation scheduling for the soils of the Guinea Savannah during 2003-2005 seasons. Also, it was used to determine some physical and agronomical parameters for the test plant (maize variety, 95 TZEE-Y) obtained from the Plant Science Department, Institute for Agricultural Research, IAR, Ahmadu Bello University, Zaria, Nigeria. The physical parameters determined were density and hydraulic conductivity while the agronomic data are water use and nitrogen use efficiencies. Others were girth and heights of plants at different periods of growth and grain yield.

The experiment was established in a field measuring 480m^2, split into 4.0 x 5.0 m plots. There were six (6) treatment water applications using gravity method. They are: 3-days, 4-days, 5-days, 6-days, 7-days and 8-days (represented as T_1, T_2, T_3, T_4, T_5 and T_6) respectively were identified and replicated four times giving a total of twenty four (24) plots using a randomized complete block design (RCBD). One polyvinyl chloride (PVC) access tube of not less than 50 cm was installed in the centre of each plots and measurements were taken daily over the growth season of March to June. The results obtained showed that the density and hydraulic conductivity were respectively 1.23-1.35 gcm^{-3} and 0.745 - 0.971 cmh^{-1}. The graphical presentations for soil water contents measured at the same depth and the grain yields obtained at three different seasons are similar. The treatment protocol, 5–days water application (T_3) is suggested and

preferred option for the production of this maize variety. This is due to the grain yield data and observed behaviour of the plants at the different growth phases in the field.

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CHAPTER 1

INTRODUCTION

The semi-arid tropics are areas where annual rainfall is less than 1300 mm with precipitation exceeding potential evapotranspiration from two to seven months annually (Malton, 1988). Semi-arid zone of Nigeria experienced annual mean rainfall amount of approximately 650 to 1300 mm (Kowal and Knabe, 1972; Ogunwole and Owonubi, 1998; Ize *et al.*, 1999). In Nigeria, the semi-arid zone covers three agroecologies namely the sahel, sudan and the Northern Guinea Savanna (Ojanuga, 2006). The primary source of water in the semi-arid part of Nigeria is rain and supports rain fed crop production in the zone. Soil moisture regime (SMR) refers to the moisture state of soil as influenced over time by either groundwater (water table) or rain water held by the soil at different tensions. The common moisture state in soil can be described as wet (saturated), moist or dry at any given time but over a period the soil moisture state may vary seasonally depending on climate or topographical location of the soil or both. However, the soil moisture regime is determined largely by climate. To this extent the soil moisture regime is commonly estimated from the gross climatic data of rainfall, temperature and evapotranspiration (Ojanuga, 2006).

Soil moisture regime is important for three reasons;-

1. Determines many of the genetic processes taking place in the soil such as weathering of minerals, leaching of nutrients and other mobile soil constituents, and accumulation of soluble salts.
2. More important than rainfall is the determinant of biologic activity such as plant growth and survival in a particular climate or region. It is used to assess the potential for growing different plants as well as the technologies needed to grow them successfully.

3. It indicates the state of aeration of, and hence the supply of oxygen in the rooting zone in, the soil.

Because of the significance to soil genesis and plant growth, soil moisture regime is used as a soil property for classifying soils at the suborder category of Soil Taxonomy.

According to manual on Agricultural Zones of Nigeria (Ojanuga, 2006) Samaru Zaria is classified to be sub-humid along with Minna-Kaduna -Kafanchan high plain. The climate of the area is designated by Ojanuga (2006) as sub-humid with total rainfall 1050 ± 228.04 mm, a distinct dry season of about 5 months duration occurring from November to March, and mean air temperatures in the months of November to February could be less than 20^{o}C, while for the months of March to May the mean air temperatures could exceed 30^{o}C (Table 1.1). The rains occur substantially from April to October generally (Ogunwale and Owonubi, 1998; Ize *et al.*, 1999). The growing season is the rainy month of April to October and has been estimated to vary from 120 days in the drier northern part (e.g. Samaru and Zaria) to 150 days in the wetter southern part (e.g. Wamba, Kafanchan and Nasarawa) (Walter, 1967).

Recent climatic data of Samaru (Kaduna state) indicates that during the season, the mean monthly precipitation varies from a low of about 65 mm in April to a high of about 350 mm in August (Ojanuga, 2006). It appears that by May, the monthly rainfall reaches and become steady at 100 mm which is considered adequate for the good plant in tropics (Udoh, 1981). The average storage capacity of the soils is assumed to be about 100 mm / meter depth of soil profile (for a sandy clay loam to sandy clay soil). Therefore, with 100 mm rainfall or more, are able to recharge soils to full capacity and these are the month of May to September (at least 5 months) in the zone. During this month crops can grow very well without moisture stress. The months (humid months i.e. June, July, August and September) that rainfall exceeds 100 mm are indeed the

months that the leaching of soil nutrients can occur. Therefore, the peak growing months are also the leaching months of soils. This has implication for fertilizer application/management in the zone.

Crop production in Nigerian Guinea savanna has been adversely affected by insufficient water supply (Jones and Wild, 1975), and crop yields are falling to very low levels and food insecurity is widespread amongst agricultural communities, because of recurrent droughts (Odunze *et al.*, 2004). Therefore, there is the need to manage available water resources for sustainable agricultural productivity in the region (Okhai *et al.*, 2000; Odunze et. al, 2001). Soil moisture however is a major limiting factor for sustainable crop production in the zone.

Normally in Samaru, rains begin in late March and establishes in late May to June, peak in August and begins to retreat untill it finally cease in October leaving the remaining part of the year dry (Ogunwale and Owonubi, 1998; Ize *et al.*, 1999). However, in other area of Northern Guinnea Savannah, such as Sokoto, Kano, and Maiduguri, rains begin in late May to June, peak in August and begins to retreat untill it finally cease in October. Rainfall in this region shows large variation both in time and space. To produce sufficient grains to feed increasing Nigerian population, dry season cultivation is encouraged. This has therefore necesitated a study on soil water measurement for maize grain production durring the peak of dry season (March - May) in Samaru Zaria (lattitude 11^{o} 11'N and longitude 07^{o} 07'E) area of Northen Guinea Savannah of Nigeria (Ize *et al.*, 1999; Iwuafor et. al, 2000; Odunze *et al.*, 2004). Efficient irrigation requires a systematic water management program. Soil water must be maintained between desirable upper and lower limits of availability to the plant. Soil moisture is an environmental descriptor that integrates much of the land surface hydrology and is the interface for interaction between the solid earth surface and life. It is a difficult variable

to measure, not at one point in time, but in a consistent and spatially comprehensive basis. Much of our failure to translate the understanding of point measurements to natural landscapes can be traced to a realization that soil moisture varies greatly in space with no obvious means to measure it. Unfortunately, long term soil moisture data sets are rare because conventional soil moisture measurement techniques, e.g., gravimetric and Time Domain Reflectometry (TDR) have historically been procedurally and labour intensive (Heathman, 1993; Thomas *et al.*, 2001; Heng *et al.*, 2002).

Fig. 1.1 Agroecological map of Zaria and other places such as Kaduna – Kafanchan – Minna with the same ecology classified as sub-humid.

Soil water measurement technique based on neutron scattering has been a valuable tool, however, training of users and safety regulation pertaining to the radioactive source in these devices make there use preventive and expensive. Other technique includes capacitance sensor and time domain reflectometry (TDR), which uses high dielectric constant property of water at high frequencies to estimate soil water content. The capacitance approach makes use of radio frequencies for determining soil dielectric constant and thus its water content while the TDR measures the propagation of an electromagnetic pulse along the transmission line (wave guides); by measuring the

travel time, the velocity and hence the apparent dielectric constant of the soil can be estimated.

Table 1.1: Rainfall and air temperature (^{o}C) at Samaru in NGS of Nigeria for 2003 – 2005.

Month/Year	2002		2003		2004		2005	
	Rainfall (mm)	Air temp. ^{o}C	Rainfall (mm)	Air temp. ^{o}C	Rainfall (mm)	Air temp. ^{o}C	Rainfall (mm)	Air temp. ^{o}C
January	0	21.5	0	13.5	0	22.8	0	24.2
February	0	25.6	0	27.6	0	24.8	0	27.2
March	19.9	30.1	19.9	29.2	13.6	29.6	0	30.8
April	69.6	31.5	31.0	32.3	7.8	30.1	63.1	31.4
May	10.6	31.7	78.4	31.0	113.5	29.4	113.1	30.3
June	133.1	28.2	69.2	27.2	190.5	27.3	160.2	27.8
July	229.0	26.6	242.3	26.2	238.0	26.2	152.6	26.1
August	210.4	26.1	427.1	25.4	302.3	25.9	235.5	25.4
September	218.8	26.7	218.7	26.2	132.1	26.5	218.5	25.9
October	125.2	26.4	67.7	26.4	20.8	25.8	65.2	26.0
November	0	24.0	0	24.6	0	24.0	0	24.7
December	0	23.5	0	24.0	0	25.4	0	23.2
Total	**1007.6**		**1154.3**		**1018.6**		**1008.2**	

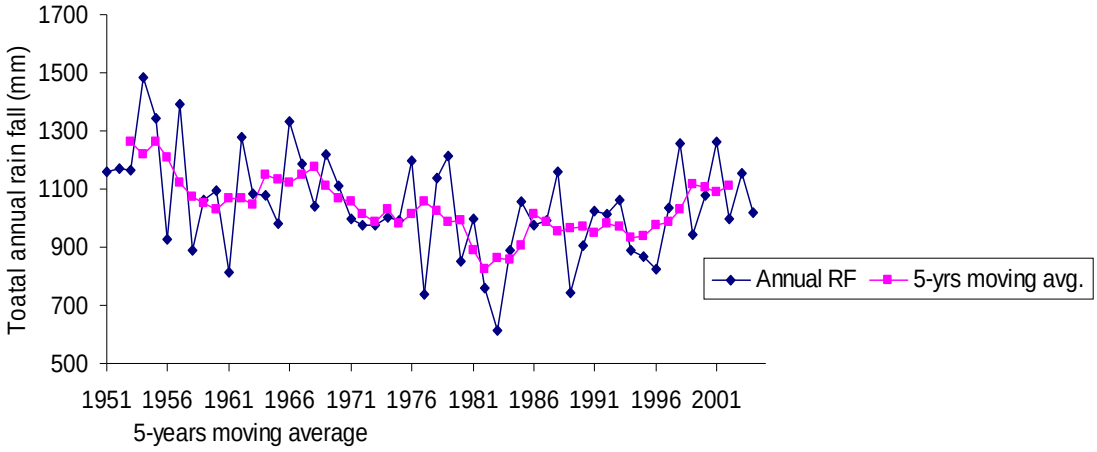

Fig. 1.2 Annual Rainfall and 5-years moving average in Samaru for 50 years.

1.1 Justification of Studies

Soil water is one of the most important requirements in agricultural production. Crop yields are generally more closely related to soil water availability than to any other soil and meteorological variable.

The growing population and improved standard of living faces agriculture with increase demands of its products. In Northern Guinnea Savannah of Nigeria, amount of water available is so limited that water becomes the limiting factor for agricultural production. The most effective way to increase food and fibre production in these regions is to find means that would help to ease the growing problem of water shotage.

Production of maize the stable food in Northern Guinea savanna of Nigerian has been adversely affected by insufficient rain and its yields have fallen to a very low level.

The effective use of soil water requires frequent and accurate measurements with a technique that is fast, reliable, simple, cost effective and non-destructive.

Green house effect; since temperature of the world is espected to increase, water evaporation from soil increases, thus decreasing soil moisture for agricultural purposes.

1.2 Aims and Objectives

Sustainability and productivity of agriculture is enhanced by developing improved approaches to managing soil, water and air resources. Therefore, aims and objectives of this study include: -

1. To identify the most efficient irrigation schedule for field crops (maize) in order to increase effective and efficient use of water in irrigation projects to achieve maximum crop growth.

2. To improve use of water supply that is insufficient in the region, because of recurrent droughts
3. Using neutron probe and electromagnetic techniques to study soil moisture.
4. To characterise the capacitance probe for suitability in Savannah Alfisols conditions for soil moisture studies, and to develop local probe materials compatible with the standard in sub-humid Savannah Alfisol.

CHAPTER 2

LITERATURE REVIEW

2.1 Soil Water Measurement Techniques

Water retention and flow dynamics in agricultural soils are primarily drivers of crop growth, nutrient cycling, and contaminant transport. Essentially, soil water is primarily for plant growth and a vehicle for solute transport including nutrient and soil contaminant (Evett and Stener, 1995; Evett, 2000; Nathan *et al.*, 2004). Accurate measurement of soil water is crucial for the better management of irrigation water and rainfall capture. Generally, crop yields are closely related to soil water available than any other soil and meteorological variables. There are various techniques for soil water measurement, but capacitance and the neutron probes are among the most recent, realiable, accurate, and fast methods develolped for soil water measurement. The capacitance probe with a trade mark of Diviner 2000 is available at the Centre for Energy Research & Training (CERT), and also the neutron probes are available at the Department of Soil Science, Institute for Agricultural research (IAR), A.B.U, Zaria, and Savannah Forestry. Other techniques of soil water measurement are Gravimetric, Tensiometric, Hygrometric, Electromagnetic, Frequency Domain Reflectometry (FDR), Time-Domain Reflectometry (TDR), Gamma radiation, Optical and Remote Sensor Technique.

2.2 CAPACITANCE PROBE (*DIVINER 2000*)

2.2.1 Introduction

Capacitance probe sensors are popular electromagnetic method for estimating soil water content (Kelleners *et al.*, 2004). The basic principle is to incorporate soil into an oscillator circuit and measure resonant frequency. However the sensors require a soil

specific calibration. Calibration studies are directly related to sensor frequency (either scaled or unscaled) to the soil water content. The sensors actually react to capacitance of soil and access tube system, which, when related to permittivity of the soil, is a function of soil water content. Measurement of the dielectric constant (ε) offers a potential and very sensitive determination of soil moisture contents. The dielectric constant for frequencies less than 1000 MHz is about 1 for air, 3 to 5 for soil particles and about 80 for water (Dean *et al.*, 1987; Evett and Stener, 1995; Evett, 2000). The relative large constant of water means that dielectric constant of bulk soil is higher when soil contains more water.

The dielectric based sensor uses differences in dielectric constants of water and soil particles in order to determine water content of a mixture of soil, water and air (Pedro *et al.*, 2001). Dielectric constant of a material arises from its polarization or electric dipole moment per unit volume. Free water molecule has a particularly high permanent electric dipole moment, which determines the high value of dielectric constant. To contribute to dielectric constant, the dielectric dipole of whatever origin, must respond to frequency of the electric field. The freedom to respond is determined by local molecular binding forces so that overall response is a function of molecular inertia, binding forces and frequency of the electric field (Dean *et al.*, 1987). Soil is a complex matrix of soil particles, air, water and solutes and molecular binding forces may be physical or chemical and consists of silica, clay minerals and humus.

2.2.2 Theory of Capacitance Probe

Probe inserted in the access tube measures capacitance of the electrode system with dielectric comprising in-situ moist soil surrounding the access tube. The probe consists of two electrodes that measure capacitance of dielectric comprising in-situ soil

surrounding a vertical PVC access tube.The two electrodes are in the form of coaxial cables which usually contains self- capacitance, C and inductance, L. For two long concentric cylinders, the electromagnetic theory shows that

$$L = \frac{\mu}{2\pi} \ln\left(\frac{b}{a}\right) \qquad (2.1)$$

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{b}{a}\right)} \qquad (2.2)$$

where b and a are radii of the inner and outer cylinders respectively, and μ and ε are permeabilility and permitivity of the insulating dielectric (Roald,1979).

Some researchers (Bell *et al.*, 1987; Dean *et al.*, 1987; Evett and Stener, 1995; Evett, 2000) give C (capacitance) of the soil-access tube system as:

$$C = g\,\varepsilon \qquad (2.3)$$

where ε is the system apparent dielectric constant and g has units of farads and a value dependant on geometry of the system. As soil water content increases, C also increase and f decreases (Pedro *et al.*, 2001). The temperature dependency is induced by temperature dependence of water's dielectric constant (assuming that the probe electronics are practically temperature insensitive).

Thus, frequency (Hz or s^{-1}) that is a property of the electromagnetic wave (EMW) is a function of the soil dielectric constant (if EMW interacts with soil matter). Also, soil dielectric constant (ε) is a function of soil water content (θ). Then, frequency is a function of the volumetric soil moisture (Dim *et al.,* 2005). Therefore, this frequency

dependency is influenced by soil composition, soil density, particle size and temperature; hence calibration is required to establish a measuring protocol for a particular soil type. Thus we can write

$$f(s^{-1}) = f_{\theta}(\theta) \qquad (2.4)$$

f_{θ} is a function of θ

Capacitance of the soil is measured by incorporating into an oscillator circuit the dielectric constant of the soil moisture and the resonant frequency (*f*) thus measured;

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (2.5)$$

A resonant LC circuit in the probe includes ensemble of soil outside the access tube, access tube itself, plus air space between the probe and access tube, as one of the capacitative elements. Changes in resonant frequency of the circuit depend on changes in capacitance of the soil-access tube system (Evett and Stener, 1995; Evett, 2000).

The total circuit capacitance in this case is made up of three components, which acts both in parallel and series (Kelleners, *et al.*, 2004);

$$C = C_m + \frac{C_p C_l}{C_p + C_l} \qquad (2.6)$$

where C_m is the capacitance of the medium, C_p is the capacitance of the plastic access tube surrounding the sensor, and C_l is the capacitance due to stray electric fields. Equation [2.5] is now in the form of

$$f = \frac{1}{2\pi\sqrt{L\left(C_m + \frac{C_p C_1}{C_p + C_1}\right)}} \qquad (2.7)$$

Since soil is part of the resonant circuit other variables in the soil will affect resonance frequency, and therefore it is necessary to suppress the effect of certain variables leaving capacitance and conductivity effects. Equation [2.7] is valid for pure dielectrics. In soil, ionic conductivity and dielectric relaxation may result in dielectric loss. The sum of these losses can be expressed as (Kelleners *et al.*, 2004);

$$G = g\sigma + g\omega\varepsilon_{rel}'' \qquad (2.8)$$

where G is sum of losses due to ionic conductivity and relaxation, expressed in Siemens, σ is bulk electric conductivity, expressed in Siemens, m^{-1}, $\omega(2\pi f)$ is angular frequency and "ε_{rel}" is loss factor due to relaxation expressed in Fm^{-1}. Equation [2.8] can be incorporated into an expression that describes resonant frequency of the capacitance probe sensor in lossy dielectrics (Kelleners *et al.*, 2004);

$$\begin{aligned}&\omega^2 C_A^2 + G^2 - \omega^4 C_s L C_A^2 - \omega^2 C_s L G^2 \\ &- \omega^4 L C_p C C_A - \omega^2 L C_P G^2 = 0\end{aligned} \qquad (2.9)$$

where $C_A = C_p + C$. The above equation [2.9] can be solved for angular frequency ω or for medium capacitance C using quadratic formula. Solving for angular frequency requires that G be estimated directly. The G term in equation [2.8] cannot be calculated analytically because ω is not known a priori. On the other hand, when solving for medium capacitance, it should be realised that C is also included in C_A. Application of

quadratic formula to solve for C therefore requires some additional but straight forward algebraic operations.

An idea of what the geometry parameter, g, refers to in equation [2.3] can be obtained from the classical equation for capacitance of a simple two-electrode plate capacitor:

$$C = \varepsilon\left(\frac{a}{d}\right) \qquad (2.10)$$

where ε is the dielectric constant, a is the area of the parallel capacitance, and d is the separation between the parallel capacitance.

Equation (2.10) however, does not hold as explained by some researchers (Dean *et al.*, 1987; Evett and Stener, 1995; Evett, 2000), because it is in the form of two cylindrical electrode plates. For capacitance probe, the soil- access tube system that forms the dielectric between the two probe electrodes is complex, and no relationship has been established for computing g and thus C for this geometry. The plates take the form of two surfaces on a cylinder separated by an insulator and access tube and soil are outside of and not between the plates. Thus, equation [2.10] is rewritten to take care of the cylindrical nature of the electrode (IAEA, 1970; Roald, 1979)

$$C = \frac{2\pi\varepsilon\ell}{\ln\left(b/a\right)} \qquad (2.11)$$

where b and a are external and internal radii of the electrode respectively and ℓ is the length of the electrode.

Thus the electric field permeating the soil forms a more or less elliptical winding around the probe with lines of force originating in one plate and ending in the other. This was

called a fringing field, although equation [2.10] does not but equation [2.11] does apply to this configuration. Any equation that does apply would have to include terms that describe the plate (electrode) surface area and the interaction of the electric field and soil column that it permeates. The latter is described by ln(*b/a*) (IAEA1970; Roald, 1979) in equation (2.11) since the simple geometry of a plate capacitor confines almost all the electromagnetic flux to volume of dielectric between the plates. For the CP electrodes, surface area of the electrodes is well known but the degree to which tortuous of electric force lines permeates the soil is not. Thus, it seems that any term equivalent to *d* i.e. {ln(*b/a*)} (IAEA1970; Roald, 1979) is particularly ill-defined in this soil access tube system since the soil, with all its variability in bulk density and water content, becomes the dielectric in the capacitive system and shape of the field may be influenced by soil heterogeneity including any gaps between soil and tube wall induced by tube installation (Evett and Stener, 1995; Evett, 2000).

The D value is difference between the resonant frequency of the probe in the access tube and a baseline resonant frequency (often measured with the probe in air).

The capacitance probe gauge is responsive mostly to a soil layer as thin as 8 cm or 12cm vertically, and within 11 cm of the probe centerline (Bell *et al.*, 1987; Dean *et al.*, 1987; Evett, 2000;). Electric field induced in the soil by CP is influenced by boundaries between soil volumes having different permittivities (Bell et. al, 1987). Some researchers (Evett and Stener, 1995; Evett, 2000) reported that when capacitance probes were buried in augured holes with direct contact between the electrode and the soil were highly sensitive to changes soil structure and texture, and provide better accuracy than the neutron probe calibrated theoretically.

2.2.3 Atomic View point of Dielectrics

There are two types of dielectric materials: polar and non-polar dielectrics. Polar dielectrics such as water have permanent electric dipole moment (EDM) while non-polar dielectrics such as carbon dioxide (Co_2) do not possess permanent dipole moment. They however, can acquire them by induction in an electric field. The non-polar dielectrics have their atomic centres of positive and of negative charges coincide at the centre of mass of the molecule, thereby making the EDM zero. The external electric field separates the positive and negative electron clouds in the atom or molecule, creating an induced EDM. Polarization occurs in material. The stored electrical energy causes a change in phase and frequency of emitted or reflected electromagnetic radiation (EMR).

The dielectric constant of a material deceases with increase in frequency. This is because of the molecular inertia to establish polarization. Therefore the decrease in the dielectric constant implies the ability to store energy decreases. There is a range of frequency over which the dielectric constant decrease and this is known as relaxation frequency. For sensors, like the CP the change in dielectric constant can be detected by measuring the change in frequency of emitted or reflected electromagnetic radiation. The frequency changes over which dielectric constant deceases are called relaxation frequency. It is in the range of kHz for ice, GHz for water and in the middle of this range for ice and water is MHz for bound water. The design and construction of any capacitance probe (CP)/sensor would depend on what form of water needs to be measured.

2.2.4 Coaxial cables

The basic geometry of a coaxial transmission lines is the outer cylinder which carries return current, and is generally made in the form of wire braid (Roald, 1979), while the dielectric material is usually of polyethylene plastic or teflon, although other materials are sometimes used. The plastic outer covering protects entire cable. One advantage of this type of construction is that the outer cylindrical conductor, besides serving as ground return, also shields the central wire from electromagnetic fields.

Two conductors separated by a dielectric (coaxial cables) usually contain a certain self-capacitance and inductance. For two long concentric cylinders, the electromagnetic theory shows that

$$L = \frac{\mu}{2\pi}\ln\left(\frac{b}{a}\right)\left[H/m\right] = 0.2K_m \ln\left(\frac{b}{a}\right)\left[\mu H/m\right] \qquad (2.13)$$

and

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{b}{a}\right)}\left[F/m\right] = \frac{55.6K_e}{\ln\left(\frac{b}{a}\right)}\left[PF/m\right] \qquad (2.13')$$

where a and b are the radii of the inner and outer cylinders respectively, μ and ε are permeability and permittivity of the insulating dielectric, $K_e = \varepsilon/\varepsilon_o$ and $K_m = \mu/\mu_o$, permittivity and permeability relative to the vacuum.

But the frequency f of equation (2.4) and characteristic impedance $Z_o = \frac{V}{I}$ which is also expressed as

$$Z_o = \sqrt{\frac{L}{C}} = 60\sqrt{\frac{K_m}{K_e}\ln\left(\frac{b}{a}\right)}[\Omega] \qquad (2.15)$$

2.2.5 Advantages:

The advantages are: -

i. very low cost and,

ii. quick response.

2.2.6 Disadvantages:

i. the presence in soil of metals has an influence on the dielectric constant,

ii. high salinity influences dielectric measurements.

2.3 Neutron Probes

2.3.1 Introduction

Soil water measurements are critical to all field studies on soil-plant water relationships. Soil water determination of soil is required in agriculture when using certain machines, when applying fertilizer, during sowing and spraying. By continuously controlling soil moisture landslides and mud streams can be forecasted and/or prevented in high mountain regions. Neutron scattering was successfully used for measuring soil water content by volume in the 1950's (Roger, 1963; Evett and Steiner, 1995; Evett, 2000). When a neutron collides with a nucleus and transfers part or all of its kinetic energy to the target nucleus without becoming absorbed by the target, it is referred to as scattering. Scattering may be elastic or inelastic; depending on whether the energy loss suffered by colliding neutron is spent on exciting or transferred to the target nucleus. The theory is based on fast neutrons which collide elastically with the nucleus of surrounding medium in the scattering process, in which:

1. fast neutrons are slowed down and
2. their course of travel is changed.

The fast neutrons emitted are slowed down until they reach thermal equilibrium with surroundings atoms (or molecules) of surrounding medium. The energy spectrum of thermal neutrons follows Maxwell-Boltzman distribution (defined as kT, which is about 0.025 eV at a temperature of 25^{o}C). It then diffuses through matter until it is finally captured by a nucleus or enters into some other type of nuclear reaction. This is the process for the formation of compound nucleus. This compound nucleus is in an excited state (10^{-12} seconds or less) and by emitting gamma radiation or proton/alpha particle

depending on the incident neutron energy i.e. $(n,\gamma),(n,p),(n,\alpha)$ reactions (IAEA, 1970).

2.3.2 Neutron Sources

Neutron is one of the fundamental particles that exist in the nucleus of every element. It is uncharged, has mass only slightly greater than that of proton (the other fundamental nuclear particle) and is unstable when free (i.e. unbound by nuclear forces); it decays with half-life of about 13 minutes into an electron and proton. Free neutrons are created through nuclear transmutation process; since none of the radioactive isotopes emits neutrons as a decay product two elements are usually involved. One of these provides energetic particles by radioactive decay and the other absorbs a proportion of these particles and decays almost immediately to produce a neutron (Greacen 1981).

Radium-226 and Americium-241 are two radioactive sources that emit alpha (α) particles accompanied by gamma rays and Beryllium-9 acts as a target to α particle, absorbs a high proportion of it and then emits fast neutrons. Radium-226 is a natural occurring element which emits a high level of energetic gamma (γ) radiation and Americium-241 is an artificial element created in a nuclear reactor with comparative low gamma (γ) radiation energy (Oresegun, 2000).

$$^{241}Am \rightarrow {}^{237}Np + {}^{4}\alpha + \gamma$$

$$^{9}Be + {}^{4}\alpha \rightarrow {}^{12}C + {}^{1}n + \gamma$$

Neurons are produced in the Am-Be source by $^{9}Be(\alpha,n)^{12}C$ reaction. If gamma radiation gives no difficulties, Ra-Be source seems the best choice, because of its

relatively low cost and stability, but health hazard must be given serious consideration (Van Bavel, *et al;* 1956).

2.3.3 Neutron Interaction with Matter

Because of their relatively small size and zero charge interactions of neutrons with matter are quite different from the interactions of charged particles and electromagnetic rays. Neutrons do not interact with coulombic field of electrons or nuclei and are, therefore, absorbed only after entering the nucleus and interacting through nuclear forces. The probability of a neutron to interact with an electron is very small.

Neutrons loose energy and interact with matter by collision reactions (scattering) and absorption reactions (capture). Nuclides have a cross section for scattering of neutrons (σ - scattering) and a cross section for capture of neurons (σ - capture). Lighter elements scatter more efficiently with neutron than heavier element, while slow neutrons are easily captured than fast neutrons.

Each of this interaction has a definite probability of occurrence, determined by the energy of the neutron and the type of nucleus (i.e. which isotope is involved). The proportion of neutrons interacting and probability that any one neutron will interact in its transit of the target is given by the ratio of total cross-sectional area to total area exposed to the neutron beam, which is given by

$$p = \sigma n ds \qquad (2.16)$$

where n is number of target nuclei per unit volume, σ is cross-section in unit of barn and ds is thickness of the target and therefore

$$\sigma = p/(nds) \qquad (2.17)$$

2.3.4 Theory of Neutron Scattering

Collisions of neutrons follow the laws of conservation of momentum. Since neutrons are not electrically charged they can lose energy only by interaction with nuclei and not by ionisation. Elastic scattering is the principal mechanism of energy loss for fast neutrons (Roger, 1963; IAEA, 1970; Leo, 1987). At energies of several MeV, the problem may be treated as non-relativistic and simply with conservation laws.

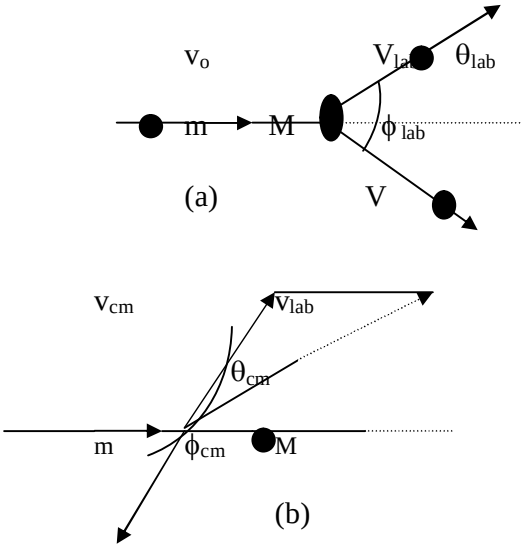

Fig. 2.1 a) Elastic scattering of neutron with nucleus
b) Frame of reference

The most important contribution to the slowing down of neutrons is elastic collision with nuclei in which the neutrons transfer some of its kinetic energy to the colliding partner. Transfer of energy is represented by the following expression when transforming from laboratory system (lab) to centre-of-mass system (cm), velocity of the neutron becomes

$$V_{cm} = \frac{A}{A + m_n} V \qquad (2.18)$$

where, $m_n = 1$ (mass of neutron), A = atomic mass number of collision nuclei, and

V = velocity of neutron before collision.

When the nucleus takes on velocity

$$V = \frac{1}{A+1} V_o \qquad (2.19)$$

After collision, the neutron takes on a new direction but retains its speed. Using cosine formula for its speed, we have

$$(V_{lab})^2 = (V_{cm})^2 + V^2 - 2V_{cm} V \cos\theta(\pi - \theta_{cm}) \qquad (2.20)$$

where θ_{cm} is the centre-of-mass scattering angle. Substituting equations (2.18) and (2.19) in (2.20), we obtain

$$V_{lab}^2 = \left(\frac{A}{A+1}\right)^2 V_o^2 + \left(\frac{1}{A+1}\right)^2 V_o^2 - 2\frac{A}{(A+1)^2} V_o^2 \cos(\pi - \theta_{cm}) \qquad (2.21)$$

since the kinetic energy (K.E) is $\frac{1}{2} m V^2$

therefore

$$\frac{E_o}{E} = \frac{(A+1)^2}{A^2 + 1 + 2A\cos\theta_{cm}} \qquad (2.22)$$

or,

$$E_o - E = \frac{2A(1-\cos\theta_{cm})}{(A+1)^2}E_o \qquad (2.23)$$

where E_o and E are respectively the energies of the neutron before and after collision.

The scattering angle in the lab system ϕ is given by

$$\cos\phi_{lab} = \frac{A\cos\theta_{cm}+1}{\left(A^2+2A\cos\theta_{cm}+1\right)^{1/2}} \qquad (2.24)$$

and the scattering parameter for the recoil nucleus is

$$E = E_o\frac{4A}{(A+1)^2}\cos^2\phi_{lab} = \frac{E_o 2A}{(A+1)^2}(1+\cos\phi_{cm}) \qquad (2.25)$$

but,

$$\cos\phi_{lab} = \sqrt{\frac{1+\cos\phi_{lab}}{2}}$$

The maximum amount of energy that can be transferred depends only on the mass of the nucleus that is participating in the collision. Thus, in a collision of a neutron with a hydrogen nucleus much of the energy of the neutron can be transferred to hydrogen nucleus, since the mass of the neutron (1.00892 a.m.u) and that of proton (1.008142 a.m.u) are nearly equal. If the participating nucleus is small, the energy to be transfer would be high. Thus, the smaller the participating nucleus, the greater the energy to be transferred. Therefore from equation (2.23) the maximum possible energy transfer resulting from a head on collision (knock on) is when $\theta_{cm} = 180^o$ and

$$E_o - E = \frac{4A}{(A+1)^2} E_o \qquad (2.26)$$

It follows from equation (2.26) that a neutron can lose all of its K.E in a single head on collision with a hydrogen nucleus. Materials containing considerable hydrogen, beryllium, or carbon are utilised as moderators in nuclear reactors.

When $\theta_{cm} = 0^o$

$$\frac{E}{E_o} = \alpha = \frac{(A-1)^2}{(A+1)^2} \qquad (2.27)$$

When $\theta_{cm} = 180^o$

$$\frac{E}{E_o} = \frac{(A+1)^2}{(A+1)^2} = 1 \qquad (2.28)$$

which shows that there is no change in neutron energy.

It is clear that the most efficient moderating materials are those of low mass number and for hydrogen, A = 1, it is possible for an incident neutron to lose all of its energy in a single head-on collision.

$$\alpha = \frac{E}{E_o} = \frac{(1-1)^2}{(1+1)^2} = 0$$

The average loss of energy per collision is one-half the incident energy

$$E = \tfrac{1}{2}(1+0)E_o = \tfrac{1}{2}E_o$$

For carbon, $\alpha=11^2/13^2 = 0.71$ so the minimum value of E is $0.17E_o$ and the average value of E if ½ $(1+0.71)E_o = 0.85E_o$.

From the above discussions, it could be seen easily that the energy of the scattered neutron is limited to the range

$$\left(\frac{A-1}{A+1}\right)^2 E_o < E < E_o \qquad (2.29)$$

where the limits correspond to scattering at $\cos\theta_{cm} = \pm 1$. For the case of proton, A = 1 and equation (2.29) becomes

$$0 < E < E_o \qquad (2.29')$$

In the centre of mass frame of reference, all scattering angle between 0^o - 180^o are equally probable, and consequently all values of E between E_o and αE_o are equally probable. The mean value of E is

$$E = \frac{1}{2}(1+\alpha)E_0 \qquad (2.30)$$

and the average loss of energy

$$E_o - E = \frac{1}{2}(1-\alpha) \qquad (2.31)$$

Thus, the lighter the nucleus, the more recoil-energy it absorbs from the neutron, which explain the case of hydrogen material such as paraffin (CH_2) or water in connection with neutron moderators and shielding. Moderators reduce neutron energies to thermal

levels in the shortest time possible. This same moderating property of hydrogen is employed to measure the moisture content of soils (Roger, 1963; IAEA, 1970; Leo, 1987).

From equation (2.23) it can be shown that, on the average, for specified nuclei, the proportion of energy lost per collision is a constant ξ, and could be written as

$$\xi = \overline{\ln(E_o / E)} = \overline{\ln E_o - \ln E} \qquad (2.32)$$

where ξ is defined as the logarithmic energy, E_o and E are the neutron energies before and after impact (Glasstone and Alexander, 1981; Hunt, 1987; Jonah, 1995).

For reactor calculation, it is often more useful to use not the average energy loss per collision but average logarithmic energy decrement per collision, i.e. the average value of $\overline{\ln E_o - \ln E}$ or $\overline{\ln E_o / E}$ which is represented by ξ.

$$\xi = \ln\left(\frac{E_o}{E}\right) = \frac{\int_1^{-1} \ln(E_o/E)\, d(\cos\theta)}{\int_1^{-1} d(\cos\theta)}$$

which on inserting the limits for $\cos\theta$ becomes

$$\xi = 1 + \frac{(A-1)^2}{2A} \ln\left(\frac{A-1}{A+1}\right) \qquad (2.33)$$

or in terms of α,

$$\xi = 1 + \frac{\alpha}{2A} \ln \alpha$$

For A greater than 10, to a good approximation

$$\xi \approx \frac{2}{A + 2/3},$$

which is clear that lighter nuclei are much more effective, per collision, in slowing down the neutrons than are the heavier nuclei.

The slowing down power (s) of a given nucleus is the product of the probability per unit time of a collision occurring and the proportion of the neutron energy obstructed, on the average per collision.

$$s = \xi \sum_s = N \xi \sigma_s$$

where N is the number of the specified nucleus per unit volume. The scattering angle is uniformly distributed in the centre of mass system and thus leads to the following conclusions (I.A.E.A; 1970):

(i) with increasing nuclear mass A the probability of back scattering increases, and

(ii) the mean distance traveled from the source before the neutron is moderated to thermal velocity can be quantified as follows

$$d = \sigma_s . \sigma_{tr}$$

where $\xi\sigma_s$ is the microscopic slowing-down cross-section, σ_s is the scattering cross-section and σ_{tr} is the transport cross-section given by

$$\sigma_{tr} = \sigma_s(1 - \bar{\mu}_o)$$

and where $\bar{\mu}_o$, in turn is the mean of the cosine of the scattering angle fixed as reference frame (Greacen; 1981). Therefore, hydrogen primarily determines the slowing down power of the medium but does not dominate its neutron transport property; the latter is greatly affected by the presence of heavier elements which, even though they produce small direct effect on the slowing down, serve to keep the scattered neutrons in the vicinity of the source.

Thermal neutron velocities in the soil approaches Maxwell-Boltzman distribution gas law.

$$n(v) = n_{th} 4\pi \left| \frac{m_n}{2\pi kT} \right|^{2/3} v^2 e^{-m_n v^2 / 2kT} \qquad (2.34)$$

where

n_{th} = total neutron density given by $n_{th} = \int_0^\infty n(v)dv$

$v_p = \left[\frac{2kT}{m} \right]^{1/2} = 2200 ms^{-1}(20.44^o C)$ which is equivalent to $E = kT$ = 1/40 eV = 0.0253 eV

The number of neutrons in a unit volume with a velocity range of dv is given by (Roger, 1963; Greacen, 1981) Maxwell distribution function

$$\frac{dn}{dv} = \frac{4n}{v_o^3 \sqrt{\pi}} v^2 e^{-v^2 / v_0^2} \qquad (2.35)$$

where $v_0 = 2kT/m_n$ and the most probable velocity per absolute temperature T, and n is the number of neutrons, m_n is the mass of neutron and k, is Boltzman constant. Thermal neutrons can be detected only by secondary charged particles, which may be protons released by collisions of neutron with hydrogen nuclei or as direct result of nuclear disintegrations produced by neutrons (e.g. alpha particle from the reaction) (Roger, 1963; Greacen, 1981).

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He \qquad (2.36)$$

Detection of neutrons is usually based on the energy of the neutron to be detected i.e. the (n, α) reaction in $^{10}_{5}B$, which has a large thermal cross section.

2.3.5 Advantages:

Once the access are in place:

1. no maintenance is required,
2. measurement can be repeated at the same location as often as required by simply taking readings from the same tube,
3. it has a relatively large radius of influence, generally between 150 mm in the wet soil and 700 mm in dry soil and
4. can measure a continuous full-depth profile through an access tube.

2.3.6 Disadvantages:

There are undesirable effects caused by (Greacen, 1981; Yuen *et al.*, 2000):

1. bound hydrogen,
2. neutron capture,

3. density variation that can induce a bias in neutron counts,
4. radiation safety hazard, which requires special licensing ,
5. inaccurate within the top soil surface (15 – 20 cm) because of escape of fast neutrons and
6. high cost of the probe discourage extensive use by individual farmers.
7. security of source – prevent theft or damage, by any unauthorized person.

2.4 Time Domain Reflectometry (TDR)

Time domain reflectometry is a method of measuring soil water content and bulk electric conductivity based on high dielectric constant property of water at high frequencies compared to other soil properties (Topp *et al.*, 1980; Evett, 2000). It measures the propagation of an electromagnetic pulse along the transmission lines (wave guides). By measuring the travel time, the velocity and hence the apparent dielectric constant of the soil can be estimated. This then allows the water content of the soil to be determined. The TDR method for soil water content measurement is widely applicable and may be used for unattended, automated data collection. Commonly used probes are bifilar or trifilar configurations that must be inserted into the soil or buried, limiting there use to near the surface in soils whose structure is disturbed by digging the pits. Probe length is limited both by conduction losses and by difficulty of insertion into soil (Evett, 2000).

2.4.1 Theory of Time Domain Reflectometry TDR

The TDR instrument converts the time measurement to length units by using the relative propagation velocity factor, V_p, which is a fraction of the speed of light in a vacuum (Topp *et al.*, 1980; Evett, 2000). For a given cable, the correct value of V_p is inversely

proportional to the permittivity, ε (dimensionless), of the dielectric (insulating plastic) between the inner and outer conductors of the cable:

$$V_p = \frac{v}{c_o} = (\varepsilon\mu)^{0.5} \qquad 2.37$$

where,

v is the propagation velocity (ms^{-1}) of the pulse along the cable,

c_o is the speed of light in vacuum (ms^{-1}),

and μ is the magnetic permeability (usually very close to unity) of the dielectric material.

The time taken for the step voltage pulse to travel along the probe rods is related to the propagation velocity as:

$$t = \frac{2L}{v} \qquad 2.38$$

where

L is the length (m) of the rods,

and the factor 2 account for the to- and fro journey.

For a TDR probe in a soil, the dielectric is a complex mixture of air, water and soil particles that exhibits an apparent permittivity, ε_a. Substituting ε_a and equation 2.38 into equation 2.37, and assuming $\mu = 1$, hence, ε_a may be determined for a probe of known length, L by measuring t:

$$\varepsilon_a = \left[c_o t \Big/ 2L \right]^2 \qquad 2.39$$

Topp *et al* (1980), stated a single polynomial function that describes the relationship between volumetric water content, θ_V (cm^3 cm^{-3}) of soils and value of ε_a determined as:

$$\varepsilon_a = 3.03 + 9.3\theta_s + 1462\theta_s^2 - 76.7\theta_s^3 \qquad 2.40$$

The impedance, $Z(\Omega)$, of a transmission line (i.e., wave guide) is:

$$Z = Z_o(\varepsilon)^{0.5} \qquad 2.41$$

where

Z_o is the characteristic impedance (Ω) of the line, when air fills the space between conductors,

and ε is the permittivity of the homogeneous medium filling the space between conductors.

For parallel transmission line (the two rods in the soil) the characteristic impedance is a function of the wire diameter and spacing (Williams, 1991)

$$Z_o = 120\ln\{2\tfrac{s}{d} + [(\tfrac{s}{d})^2 - 1]^{0.5}\} \qquad 2.42$$

where

s is the spacing (m), and

d is the wire diameter (m)

or, if $d << s$:

$$Z_o = 120 \ln(2 s/d) \qquad 2.43$$

For a coaxial transmission line (Topp *et al.*, 1980), the characteristic impedance is:

$$Z_o = 60 \ln(D/d) \qquad 2.44$$

where

D is the diameter of the outer conductor.

From equations 2.41 – 2.44, it is apparent that impedance, Z, increase as wire spacing increases, and decreases as ε (or water content) increases for any probe type.

2.5 Methods of Access Tube Installation and Measurements

Sub - surface probes for soil moisture measurements are mostly introduced into the ground through access tubes which are left in position as long as measurements are required. Access tubes are installed with a steel liner and cutting head operating through a guide plate to prevent lateral movement (Plate 2.1) and the creation of air gaps between soil and tube (Greacen, 1981; Thomas, *et al.* 2001).

Plate: 2.1 Soil augering

Access tube is made tight fit in the soil along its whole length so that water does not enter air gap between a loose fitting tube and the soil resulting in greater wetting near the tube. This is avoided by techniques used for soil removal and from driving access tube in the hole. Access tube installation is also done so as to eliminate air gaps between the tube and soil and minimize soil disturbance. It is essential to avoid permanent error during installation of access tubes so that it does not introduce permanent error to the soil water measurements (Dean *et al.,* 1987; Bell *et al.*, 1987; Evett &Steiner, 1995; Evett, 2000). The decision on size and type of material for access tubes is determined by diameter of probe in use, cost and availability of tubing, and presence of corrosive substances in the soil. The internal diameter of access tube should be as small as possible to reduce error due to eccentric positioning of the probe, but still allow it to move freely. Access tubes are sealed at the bottom with a rubber bung to avoid ingres of water into the tube and when not in use, covered with a removable cap to prevent ingres of rain and dirt. Aluminium tubbing is preferred to neutron probe as it is transparent to

neutrons and does not affect sensitivity, but corrode in acid or alkaline soils and as such need replacement after a long-term experiment (Greacen, 1981; Thomas *et al.*, 2001). Sensitivity of the neutron probe is reduced when a steel or brass access tube is used owing to absorption of slow neutrons by iron and copper. Polyvinyl chloride (PVC) which is preferred for capacitance probe is not recommended for neutron probe because of the presence of chlorine which has a larger slow neutron absorption cross-section resulting in a reduction of the count rate and sensitivity experiment (Greacen, 1981; Roger 1963; IAEA, 1970; Corbeels *et al*., 1999; Thomas *et al.*, 2001).

2.6 Gravimetric Soil Sampling

Soil sampling is the only direct method for measuring soil water content. It is the most accurate method which is often used for calibration of other techniques. The approach requires careful sample collection and handling to minimize water loss between the time a sample is collected and processed. In most cases replicated samples are usually taken to reduce the inherent sampling variability that result from the volumes of soil.

The equipment required for soil sampling includes a soil auger or a core sampler (with removable sleeve of known volume to obtain volumetric water content), sample collection cans or other containers, a balance accurate to at least 1 gram and a drying oven.

Soil samples are taken from desired root zone and temporarily stored in water vapor-proof containers. The samples are then weighed and the open containers are oven dried for 48 hours at a temperature of 105^{o}C. The dried samples are then re-weighed. Percent soil water content on a dry mass or gravimetric basis, P_w, is determined with the following formula

P_w = [(wet weight-dry sample weight)/dry sample weight] x 100

The difference in the wet and dry weights is the weight of water removed by drying. In converting from a gravimetric basis to water contents on a volumetric basis, P_v, we multiply the gravimetric soil water content by soil bulk density (BD). Soil bulk density is the weight of a unit volume of oven dry soil usually determined in a manner similar to that of gravimetric sampling.

BD = weight of oven dry soil / unit volume of dry soil

$P_v = P_w \times BD$

Soil water content on a volumetric percentage basis is a preferable unit for irrigation management. Comparison of the measured volumetric soil water content with field capacity and wilting point of the soil is used to determine the available soil water and the percent of total available soil water.

2.6.1 Advantages:

1. Only direct and accurate methods for calibrating other techniques
2. Information on soil layering and compaction, changes in soil texture etc are found in the process.

2.6.2 Disadvantages:

1. Gravimetric sampling is time consuming and labour intensive.
2. The results are generally not known for a minimum of 48 hours after sampling.
3. Usually, large samples are taken each time sampling is done to remove the inherent variability of this approach.
4. Samples cannot be taken from exactly the same point on subsequent sampling dates.
5. It can be expensive if substantial and repetitive sampling is required.

2.7 HYDRAULIC CONDUCTIVITY

The hydraulic conductivity of a soil is a measure of the ease at which water moves through the soil. It can be obtained by measuring the flux density of water passing through a soil and is the proportionality constant which when multiplied by the driving force causing water to move gives the flux density of water.

The soil-water transmission properties of a soil are measured by its hydraulic or proportionality constant. Hydraulic conductivity indicates how well fluid will flow through a substance, e.g. rock or gravel. The estimation of hydraulic conductivity is essential for the determination of soil water fluxes and hence water balance in the soil profile (Vose, 1980; Genuchten van 1980; Marshall *et al.*, 1988). Accurate soil water content measurements are required for measurements of crop water use and of the hydraulic characteristics of soils. Soil hydraulic conductivity (K) – water content (θ) – pressure head (h) are key parameters for crop growth, irrigation, drainage, and modeling water flow and chemical transport through the soil. A sound irrigation management program considers the soil physical properties, such as, soil water – holding capacity and hydraulic conductivity to determine the timing and amount of irrigation water to be applied (Libardi *et al.*, 1980; Vose, 1980; Fares *et al.*, 2000).

2.7.1 Theory of Hydraulic Conductivity

The hydraulic conductivity is the volume of flow in unit time per unit cross-sectional area divided by the hydraulic gradient. Expressions for hydraulic conductivity is derived from Darcy's equation (Rose *et al.*, 1965; Genuchten van 1980; Marshall *et al.*, 1988),

$$q_L = -K(\theta)\frac{dH}{dz} \qquad 2.45$$

where, $K(\theta)$ = hydraulic conductivity at depth z = L

q_L = steady state flux of water passing through a unit soil surface per unit time

$\frac{dH}{dz}$ = total water potential gradient.

For non-steady conditions, the rate of change in water content $\frac{d\bar{\theta}}{dt}$ is

$$\frac{d\bar{\theta}}{dt} = \frac{d}{dz}\left[K(\theta)\frac{dH}{dz}\right] \qquad (2.46)$$

which, on integration gives (Libardi et al 1980; Das *et al.*, 2002)

$$L\frac{d\bar{\theta}}{dt} = \left[K(\theta)\frac{dH}{dz}\right]_{z=L} - \left[K(\theta)\frac{dH}{dz}\right]_{z=0} \qquad (2.47)$$

where, $\bar{\theta}$ = mean soil water contents (cm^3cm^{-3}), the first term on the equation [2.47] is the water flux across depth L ($cm^3cm^{-2}day^{-1}$) and the second term is the water flux across the soil surface ($cm^3cm^{-2}day^{-1}$).

It is however clear that, in many cases after irrigation or heavy precipitation the major part of the water will be drained out of the profile at depth L, while water evaporating at the soil surface will be small in comparison, and the second term is therefore ignored. And equation [2.47] takes the form

$$L\frac{d\bar{\theta}}{dt} = \left[K(\theta)\frac{dH}{dz}\right] \qquad (2.48)$$

It has been shown in practice that little is lost by estimating dH/dz as –1 (Libardi *et al.*, 1980; Vose, 1980), giving:

$$K(\theta) = -L\frac{d\bar{\theta}}{dt} \qquad (2.49)$$

There are several approaches to the measurement of soil hydraulic conductivity in the field (Green and Corey, 1971; Libardi *et al.*, 1980; Kirda, 1990). One of which necessitates soil water tension measurements in addition to the rate of soil water content decrease within the soil water profile. This equation can be used to calculate the hydraulic conductivity

$$K(\theta) = \left[L\left(\frac{d\theta}{dt}\right)\right] / \left(\frac{dH}{dz}\right) \qquad (2.50)$$

where dH/dz is the hydraulic gradient measured at soil depth L using tensiometers.

However K is related to θ as described by Libardi *et al.*, (1980); Jones and Wagenet, (1984) with the following equation.

$$K(\theta) = K_o \exp[\beta(\theta_o - \theta)] \qquad (2.51)$$

where β is a constant and K_o and θ_o are the values of K and θ at saturation, respectively.

The values of β and K_o are to be calculated using the field data and the relation

$$\ln[z(d\theta/dt)] = \beta(\theta_o - \theta) + \ln K_o \qquad (2.52)$$

a semi-log plot of the absolute value of $z(d\theta/dt)$ against $(\theta_o - \theta)$ gives β and $\ln K_o$ from the slope and intercept, respectively (Libardi *et al.*, 1980).

CHAPTER 3

Physical Environment and Experimental Field Development

3.1 Development of a Field

Samaru Zaria lies within the lattitude of 11^{o} 11'N and longitude of 07^{o} 7'E area of Northen Guinea Savannah of Nigeria (Iwuafor et al., 2000; Odunze et al., 2004). The climate of the area is sub-humid with total rainfall 1050 ± 228.04 mm, a distinct dry season of about 5 months duration (November to March), and mean air temperatures in the months of November to February could be less than 20^{o}C, while for the months of March to May the mean air temperatures could exceed 30^{o}C. The experiment was conducted at Center for Energy Research and Training (CERT) farm Ahmadu Bello University, Zaria. The field was divided in to equal size of blocks and each block is subdivided into plots such that there is one plot for each treatment in each block. Within each block, the allocation of treatments to plots is done randomly (Wardlaw, 1987). A random sample has the best chance of being representative of the population (Erwin et al., 1962).

Randomised Complete Block (RCB) design is one of the most widely used experimental designs in agricultural research. The design is special by suited for field experiments where the number of treatment is not large and the experimental area has a predictable productivity gradient. The primary distinguishing of RCB design is the presence of

blocks of equal size each of which contains all the treatments (Gomez and Gomez, 1984; Wardlaw, 1987).

3.1.1 Farm Layout and development

The experimental layout is the randomised complete block design (Table 3.1) with six treatments, replicated four times. Treatment was identified on the bases that maize plant would not be stressed for more than 10 days with out water. So treatment was identified as 3, 4, 5, 6, 7 and 8 days after water application.

Table: 3.1 Randomised block design plot containing treatments

T_1	T_4	T_2	T_3
T_6	T_5	T_5	T_6
T_4	T_3	T_6	T_4
T_3	T_1	T_1	T_1
T_2	T_6	T_4	T_5
T_5	T_2	T_3	T_2

The treatments are: T_1, 3-days after irrigation; T_2, 4-days after irrigation; T_3, 5-days after irrigation; T_4, 6-days after irrigation; T_5, 7-days after irrigation; and T_6, 8-days after irrigation. Net plot size measures 5m by 4m /replicate/block. The total net block size therefore is $480m^2$. Each subplot has 6 ridges with four middle ridges as net plot. In each replicate, the six treatments (T_1, T_2, T_3, T_4, T_5 and T_6) are represented. In each block, one variety of maize is planted and used to study and characterise the capacitance probe (*Diviner 2000*). The maize variety used is 95TZEE-Y, which was obtained from Department of Plant Science, Institute for Agricultural Research (IAR), ABU, Zaria. Irrigation water is supplied between furrows in plots using the gravity method, and. Climatological data of the area were carefully measured and compare with that obtained from the Institute for Agricultural Research (IAR)/ABU, Zaria.

In each subplot an access tube was installed at the centre. A total of 20 access tubes were installed for 2003 season and 18 access tubes for 2004 and 2005 season. The

subplots were numbered from the left consecutively and continuously to identify the measurement point in the instrument (Diviner 2000) as profiles starting from 10 through to 33.

Table: 3.2 Subplot containing Treatments and corresponding Profiles

T_1 (10)	T_4 (21)	T_2 (22)	T_3 (33)**
T_6 (11)	T_5 (20)	T_5 (23)	T_6 (32)**
T_4 (12)	T_3 (19)	T_6 (24)	T_4 (31)**
T_3 (13)	T_1 (18)	T_1 (25)	T_1 (30)**
T_2 (14)	T_6 (17)	T_4 (26)	T_5 (29)*
T_5 (15)	T_2 (16)	T_3 (27)	T_2 (28)*

Note: ** no access tubes for three seasons and
* no access tubes for two seasons

3.1.2 Furrow and sub-plot design

There are 24 plots (as shown in Table 3.1) in the field of which each measured 5.0 m x 4.0 m in size. The net area of the block is 480m^2 while the total area of the block is 648.8 m^2. 0.75 m boarders pathways were created between the plots to allow free movement within the field. There were six ridges per sub-plot with seventeen (17) to eighteen-(18) maize plant (95 TZEE-Y) per ridge. The space between the ridges is about 0.75m.

After the initial ponding and field capacity were attained, water was given to the plant at 3, 4, 5, 6, 7 or 8 days after water supply which correspond to T_1, T_2, T_3, T_4, T_5 and T_6 treatment respectively (see appendix A1, A2 and A3). The whole farm was ponded and allowed to stand for two days to attain field capacity.

96.0 litres water was applied to each furrow at the day of treatment using gravity method (see plate 3.5) this is obtained through 6 graduated 16.0 litres bucket. These

buckets were used to supply water to the furrow via local and supervised labour. This method is fast; about 15 minutes is required to pond a sub-plot.

3.2 Access Tube Installation and Materials

One polyvinyl chloride (PVC) access tube (5.1 cm internal diameter (ID) and 5.6 cm external diameter (OD)) was installed to a depth not less than 30.0 cm and not greater than 60.0 cm (30.0 cm ≤ depth ≥ 60.0 cm) in the centre of each plot. An over sized hole of about 5.62 cm OD i.e. 2.0 mm in diameter larger than access tube was drilled with a hand operated screw auger. Access tubes were installed with a steel liner and cutting head operating through a guide plate to prevent lateral movement (see plate 3.3) and the creation of air gaps between soil and tube (Greacen, 1981; Thomas, et. al 2001). The access tube was made tight fit in soil along its whole length so that water does not enter air gap between a loose fitting tube and the soil resulting in greater wetting near tube (see plate 3.1). This was avoided by techniques used for soil removal and from driving the access tube in the hole.

The access tubes were sealed at the bottom by rubber bung (improvised in most cases - see plate 3.4) to prevent ingress of water/soil into access tube and covered at the top by removable cap (empty tin can of milk). The readings were taken daily at 10.0 cm 20.0 cm 30.0 cm 40.0 cm 50.0 cm and 60.0 cm depths depending on the length of each access tube. At the irrigation day, readings were taken twice in each irrigated plots 5 to 6 hours after irrigation.

Plate 3.1: Installation of the Access tube in the field

The diameter of probe in use determines the size and type of material for access tubes. Aluminium tubing is preferred for neutron probe as it is transparent to neutrons and does not have an effect on sensitivity, but corrode in acid or alkaline soils and as such need replacement after a long-term experiment. Sensitivity of the neutron probe is reduced when a steel or brass is used owing to absorption of slow neutrons by iron and copper.

Polyvinyl chloride (PVC) which is used for capacitance probe (see plate 3.2) is not recommended for neutron probe because of the presence of chlorine which has a larger slow neutron absorption cross section resulting in a reduction of count rate and sensitivity.

Plate: 3.2 Access tube materials ready for installation in the field

Plate 3.3: Soil augering for access tube installation

Plate 3.4: Improvisation of Bung/Stopper

3.2.1 Watering scheduling

Initially, tap were laid in the field with the idea that there would be water regularly. Unfortunately, water at that time of the year (i.e. February to May) is usually a problem. This has necessitated the purchase of water tank reservoir and request for water tanker to bring water for storage in those tanks. However, in the year 2004, the Center for Energy Research and Training (CERT) purchase a tractor/tanker which assisted us greatly. Six plastic buckets were purchased from Samaru market. These buckets were calibrated in the laboratory and used for watering. 96.0 litres of water were applied to each furrow at the day of treatment using gravity method (see plate 3.5) via local and supervised labour. This method is fast; about 15 minutes is required to pond a sub-plot.

Plate 3.5: Ponding using gravity methods with 96.0 litres of water per furrow

3.2.2 Measuring scheduling

Initially, measurements with *Diviner 2000* in the field were schedule for morning and evening. In the morning, the measurements were taken between 8:00 am – 9:00am and in the evening 4:00 pm – 6:00 pm. It was later discovered that one measurement per day was adequate for the Diviner 2000. For treatments that required to be irrigated, measurements were taken between 8:00 am – 9:00 am before irrigation was done. Measurements were taken regularly during the different growing stages of the plant.

3.2.3 Planting arrangement

Two seeds of maize (95 TZEE-Y) were planted at the base of the ridge, at 25 cm by 75 cm, and thinned to one plant per stand at 2 weeks after planting (see plate 3.6). It was not planted on the ridge because of the watering procedure employed. The maize variety (95 TZEE-Y) was planted at alternate side of the ridge, except for the last ridge, in which both side were planted.

Plate: 3.6 Ridges and furrow with germinated plant and installed access tubes

3.2.4 Application of Fertilizer

Fertilizer was applied in two splits with half dose at the first application using NPK (15: 15: 15). The second application (topdressing) of 60 kg N $ha^{-1}$was made at four weeks after planting using Urea (46%); thus attaining the recommended rate of 120kg N ha^{-1}, 60 kg P_2O_5 ha^{-1} and 60 kg K_2O ha^{-1} fertilizer for maize (*Zea Mayas* L*)* in the ecological zone. This correspond to about 38.7 Kg of NPK (15:15:15) to the 24 plots and 7.5 g per stand which was applied 2 weeks after planting and 46 % urea (2.3 g per stand) 2 weeks after the first application (4 wks after planting). Application of fertilizer is done after weeding (see plate 3.7).

Plate 3.7: Weeding on the 05 04 03

CHAPTER 4

Material and Methods

4.1 Pre-Test of Capacitance probe (*Diviner 2000)* (Standardization)

The capacitance probe (*Diviner 2000*), provided has been calibrated from factory. This has therefore necessitated field calibration of *Diviner 2000* to suit the soil for standardization of the equipment. Soil sampling which is the only direct method of measuring soil water content is also the most accurate method of calibration of other techniques is therefore used for calibration of capacitance probe *(Diviner 2000).*

4.1.1 Experimental procedure

Three (3) sites which give representative sample of the area were selected and two access tubes of one to two metres apart are installed at each site. The three (3) sites are dry, moist and wet site. Tubes in these sites are destructively sampled. For wet site, wettest time gives a better result of sampling; however this could be supplemented by liberal irrigation (ponding). Sampling other tube of each pair for the dry end of the range should be done at end of dry season or by erecting a shelter over each profile of the dry site to prevent wetting by rain.

The scale frequency in the soil is measured with *Diviner 2000* in each access tube at 10, 20, 30, 40 and 50 cm. Three sampling core are placed very closed to the access tube and centered at selected depth following strict sampling procedure by digging a trench and preparing a level surface at each depth. Alternatively, sampling core may be taken carefully by removing the over burden with a posthole digger or auger (Greacen, 1981; Akhter, *et al.,* 2000; Baba-Kutigi, *et al.*, 2006). Samplings are done as quickly as possible to preclude significant changes in volumetric water contents (θ) between determine scale frequency (SF) and taking the samples. Sample cores are usually

covered with plastic caps to preclude moisture loss from the samples. The mass is obtained by drying the sample at 105^{o}c to a constant weight, and the volume is that of the core sampler.

Volumetric water contents (θ) and bulk density (ρ) of the sample cores are determined, through which calibration is established.

Bulk density (ρ) is thus obtained from the data which is the ratio of the mass of a given sample to its bulk volume.

Bulk density (ρ) = M_d/V (gcm^{-3}).

Gravimetric water content (W) = $(M_w - M_d)/M_d$ (gg^{-1})

Volumetric water contents (θ) = Wρ

where,

M_w = wet mass of soil core (g),

M_d = dry mass of soil core (g) and

V = bulk volume (cm^3)

The three (3) readings taken from each profile at required depth are not averaged. The scale frequency (SF) is

$$SF = \frac{f_a - f_s}{f_a - f_w}$$

where: - f_s = sensor frequency in soil

f_a = sensor frequency in air

f_w = sensor frequency in water

The sensor frequency is scaled because not all sensors behave exactly the same (Paltineanu and Starr, 1997; Kelleners et al. 2004).

4.1.2 Precautions

It is important to take the following precaution which will reduce the error encountered during the experiment: -

i) Area of the cross-section of metal to that of soil should be lees than 0.1;

ii) Soil above the sampling depth is removed without compressing the layer to the volume sampled;

iii) Level of the top of soil inside the sampler does not move during driving.

4.1.3 Result

The volumetric water contents θ_v determine from the graph is

$$\theta_v = 0.422(SF)^{1.5781}$$

This is comparable to the factory calibration (Syntek, 2000) which is

$$\theta_v = 0.490(SF)^{2.1674}$$

Equating the two volumetric equations and neglecting the coefficients

$$(SF)^{1.5781} = (SF)^{2.1674}$$

which shows that the scale frequency (SF) to be approximately 0.8.

The *Diviner 2000* can effectively be used in the field as it has been calibrated and found to be in line with factory calibration.

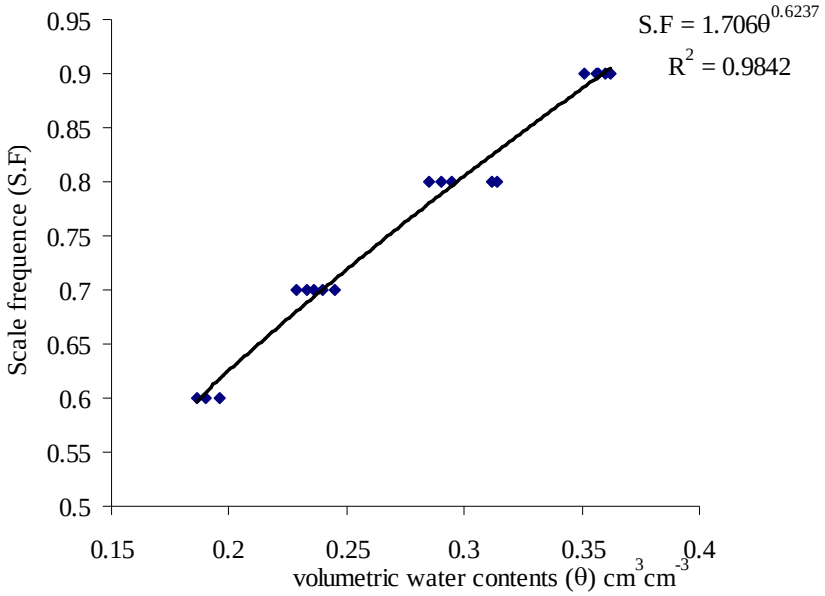

Fig 4.1 Field Calibration using Diviner 2000

4.2 Hydraulic Conductivity

Hydraulic conductivity of a soil is a measure of the ease at which water moves through soil over time. It can be obtained by measuring the flux density of water passing through a soil and is the proportionality constant which when multiplied by the driving force causing water to move gives the flux density of water.

Five plots of 5.0 m x 4.0 m were prepared with six ridges each. A PVC access tube (5.1 cm ID and 5.5 cm OD) was installed to a depth of not less than 30 cm in each plot using hand held auger. The furrows of the ridges were ponded with 120 liters of water each. The soil surface was covered with grass to reduce water loss by evaporation or water input by rain. Soil water content was measured at 10, 20 and 30 cm soil depths over a 5 days period. The readings were taken twice daily, one at about 9.00 am and the other at

about 3.00 pm. The experiment took place at the farm site of Center for Energy Research and Training (CERT), Ahmadu Bello University, Zaria (Baba-Kutigi, *et al.*, 2006). This was done with a capacitance probe with a trade name called *Diviner 2000*. The *Diviner 2000* is a hand-held, portable soil moisture-monitoring device consisting of a portable display/logger unit, connected by cable to an automatic depth sensing probe. During the measurement the probe is inserted into an access tube, a high frequency electrical field (>100 MHz) which is created around the sensor and extends through the access tube allowed the moisture to be determined. The method utilizes high dielectric constant of water compared to soil and air to determine water content of the soil. A pair of electrodes or electrical plates (which can be parallel spikes or circular metal rings) was used as capacitor. When activated, the soil-water-air matrix around the PVC tube forms dielectric of a capacitor and completes the oscillating circuit. Changes in the resonant frequency of the circuit depend on changes in capacitance of the soil access tube system (Dean *et al.*, 1987; Paltineau and Starr, 1997; Fares and Alva, 1999; Fares *et al.*, 2000; Heng *et al.*, 2002).

CHAPTER 5

Results and Discussion

5.1 Deductions from moisture measurement curves

Water is the only variable applied as treatments (T_1, T_2, T_3, T_4, T_5, and T_6) corresponding to three (3) days, four (4) days, five (5) days, six (6) days, seven (7) days and eight (8) days water application respectively. Each treatment has four plots, however, only three plots have access tube install. The readings are taken using capacitance probe (*Diviner 2000*) daily for about 10 weeks for three seasons (2003, 2004 and 2005). Reading for the profiles in three seasons for particular treatment shows similarities in rise and fall.

For treatment 1 (T_1 - 3 days after irrigation), during the sixth week, the plots are wet, simulating a situation of adequate moisture for the plants. The plants are tassling, flowering and looking greenish. The gaits are satisfactory and well close to 3.40 cm thick.

In the sixth week of life of the plants (i.e. plant establishment stage), T_6 - 8 days after irrigation was seriously stressed by end of 6-7 days (i.e. there is decline in soil water which results to onset of crop water stress). It had used up ~ 50% of the moisture available to it in the depth levels 0-30 cm. The amount of moisture available at depth levels 40-60 for instance sometimes is close to 90%. This moisture level does not seem to be available for plant to survive well to the wetting day.

The figure 5.2 show that variations in measurement are much noticed in the first 10 cm more than 20 cm and almost constant for 30 cm. This is applicable to other profiles. This suggests that most root activity for maize is within 30 cm and intake of water by

the root is more in the first 10 cm. The capacitance probe can be used for the measurement of soil moisture at soil surfaces.

5.1.1 **Discussion on measurements**

Water is the only variable applied as treatments (T_1, T_2, T_3, T_4, T_5, and T_6) to maize plant keeping fertilizer application uniform for all treatments. The readings were taken for three seasons (2003, 2004 and 2005) using capacitance probe (Diviner 2000) daily for about 10 weeks. The reading for the profiles in three seasons for particular treatment shows similarities in rise and fall.

Table 5.1 Deductions from the ANOVA and Descriptive statistics for 2003

Treatment	Profiles	Standard Error	Standard Deviation	Confidence Level (95%)	F	P	F critic
	10	0.320	3.193	0.654			
1	18	0.307	2.934	0.612	30.75	8.92×10^{-13}	3.029
	25	0.269	2.581	0.535			
	14	0.374	3.552	0.744			
2	16	0.395	3.730	0.786	63.83	1.24×10^{-32}	2.631
	22	0.164	1.357	0.328			
	28	0.169	1.608	0.337			
	13	0.204	1.890	0.406			
3	19	0.205	1.910	0.409	37.99	3.62×10^{-15}	3.031
	27	0.166	1.539	0.330			
	12	0.376	3.469	0.748			
4	21	0.189	1.741	0.376	711.26	2.3×10^{-104}	3.032
	26	0.080	0.737	0.159			
	15	0.288	2.640	0.573			
5	20	0.121	1.106	0.240	45.13	1.72×10^{-24}	2.632
	23	0.216	1.978	0.429			
	29	0.229	2.094	0.455			
	11	0.446	4.066	0.888			
6	17	0.205	1.871	0.409	302.96	4.42×10^{-67}	3.032
	24	0.181	1.648	0.360			

Analysis of variance (ANOVA) and the descriptive statistics of measurement in 2003 show similarities in F critic of which all treatments with three profiles (T_1, T_2, T_3, T_4,

T_5, and T_6) has a value of 3.03 while those with four profiles (T_2 and T_5) has values of 2.63. The P-value for all treatments is less than 0.0001. The standard error for the treatment 1 has range from 0.269 to 0.320 while it has the standard deviation of 2.581 and 3.193.

There are similarities in rise and fall of moisture contents measurements for three seasons (2003, 2004 and 2005). It is observed that, the treatment given does not matter in the first four weeks so long as maize (*Zea mays L.*) plants germinate appropriately. At the tassling period, no matter the treatment the graph begins to falls. When it begins to rise it shows the sign of maturity that the plant does not need much water at that period again. Crop water requirements vary with stage of growth. The most critical growth stage in maize (*Zea mays L.*) is the flowering and post-flowering period around 2 days before 22 days after silking (Dennis et al., 2001). This is the period in which water is needed by grain filling and should be taken seriously.

Tolerance of maize to stress from drought is related to development of the root system, which in turn influences water and nutrient uptake by the crop plant. A number of studies have shown that water uptake from a given volume of soil depends on the rooting density and soil water properties (Kamara *et al*., 2001) that provide better tolerance to drought and nutrient stress, thereby stabilizing maize yield under stress conditions.

5.2 Daily Soil Water Changes

The daily soil water changes at 10 cm and 20 cm are quite pronounced. At 30 cm the changes become more subtle and at 40 cm, 50 cm and 60 cm they are non existence. Soil water extraction pattern provides information about the part of root zone actively involved in soil water uptake. According to the dynamics described in figure 4.2, the

bottom of active root zone is at 30 cm. Root activity is more pronounced at shallower depths of 10 cm and 20 cm soil depth. That is the daily soil water change pattern for profile 11 (T_6).

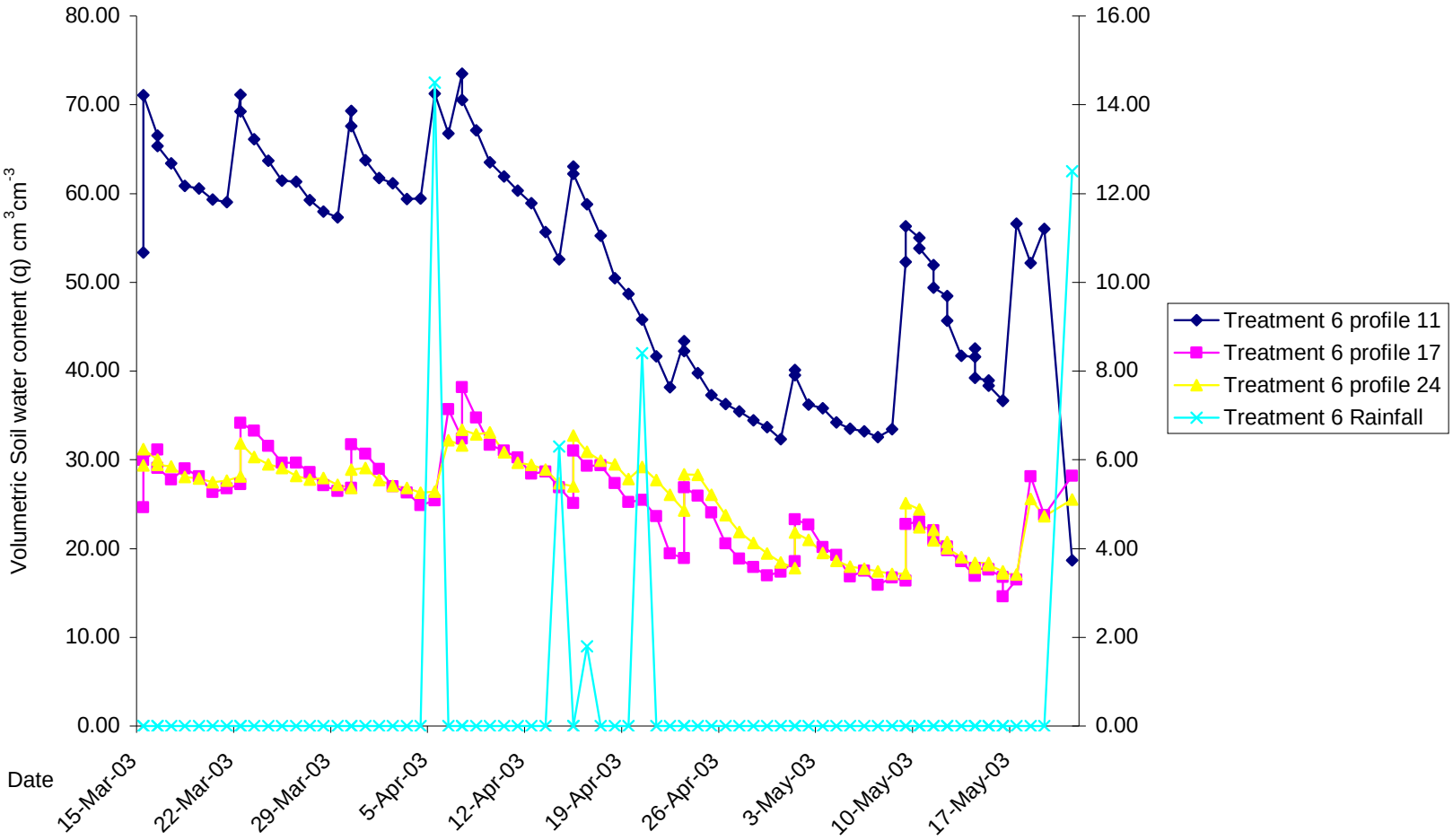

Fig. 5.1 Daily Soil Water changes for maize ABU IAR 95 TZEE-Y Treatment 6

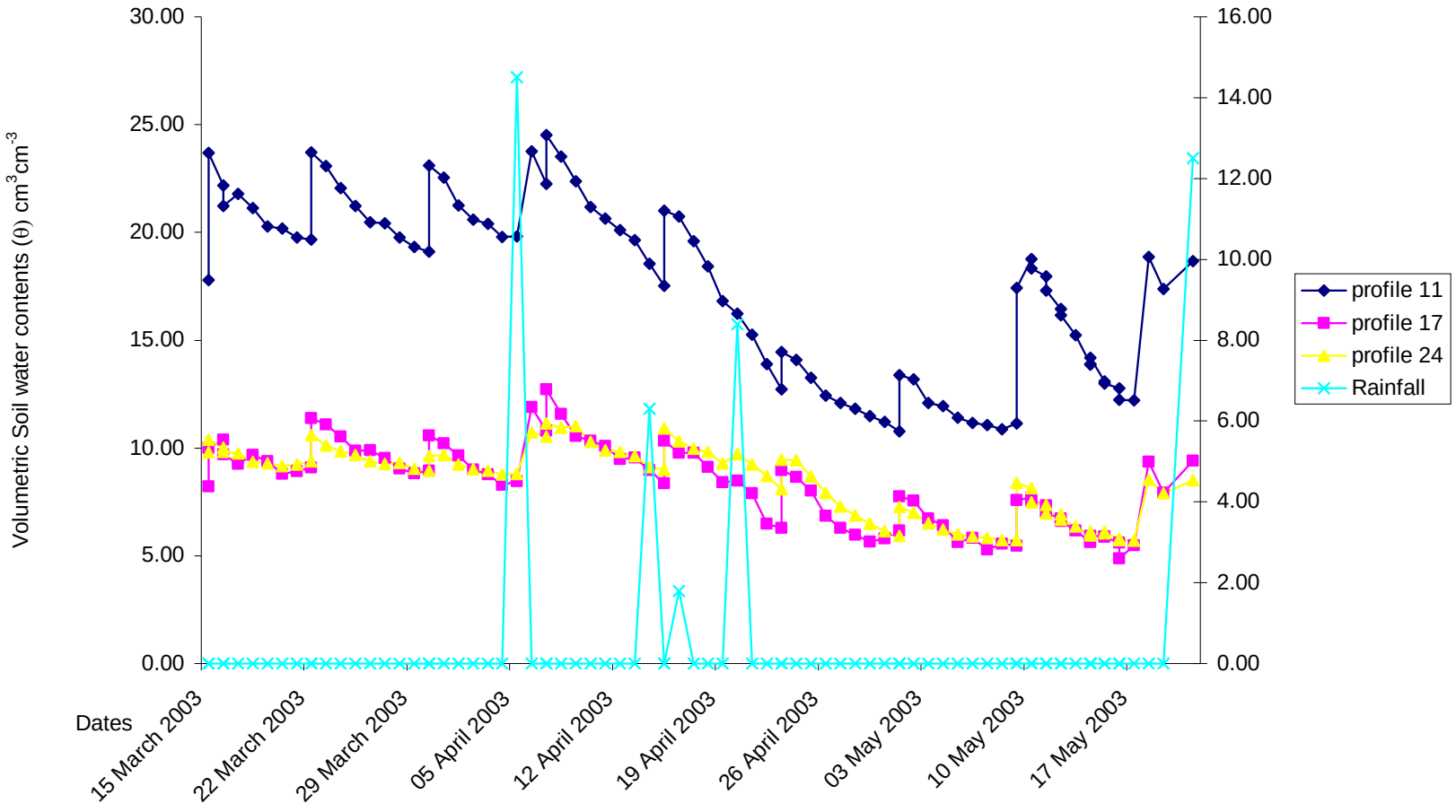

Fig. 5.2 Daily soil water changes ABU IAR 95 TZEE Y Profile 11 Treatment 6

5.3 Irrigation Scheduling

It is usual practice to use available soil water content as a criterion for deciding when irrigation is needed. Soil water content is determined by using soil measuring techniques such as capacitance or neutron probe that can describe the depletion of available soil water rather accurately.

The irrigation scheduling is based on water treatment (i.e. T_1, T_2, T_3, T_4, T_5, and T_6) that decides when to irrigate and observe behaviour of the maize plants and yields for three seasons 2003, 2004 and 2005. Since maize (95 TZEE-Y) developed specifically for regions with annual low rain fall, its length of growing period (LGP) is about 11 weeks for it to mature. 480 litres of water is applied to each plot in its treatment days. Thus the total water applied to each plot for the maize to reach its maturity is

Total water applied by irrigation (mm)	=	water applied to a plot x (7/treatment days) x the length of growing period (LGP) (11 weeks)
Water applied to a plot at ponding day	=	24 mm

5.3.1 Irrigation measurements

Capacitance probe is used to determine available soil water contents as a criterion for deciding when irrigation is needed as it can describe the depletion of available soil water rather accurately. The irrigation scheduling is based on water treatment (i.e. T_1, T_2, T_3, T_4, T_5, and T_6) in which 24 mm of water is applied to a plot at treatment days for about 11 weeks. When water treatment is given, soils are wetted to saturation, which means all soil pores are filled with water. Drainage through this profiles proceeds at a

rate determined by soil structural attributes, slowing appreciably after 1 – 2 days non clay and or loam soils. The change in volumetric soil moisture content is due to the processes of drainage and evapo-transpiration. Plant Available Water (PAW) describes the amount of water extracted by a crop between the field capacity and permanent wilting point. Readily Available Water Capacity (RAWC) is preferred for use in irrigation scheduling because it defines lower limit (onset of crop water stress) and is an exact irrigation trigger index of the crop that signals onset of water stress from a crop's point of view. The slow down of daily soil water changes should correlate only with the starting difficulties of the plant to develop sufficient osmotic pressure to extract soil water from a diminishing soil water reservoir. Crop water requirements vary with stage of growth.

5.3.2 Plant water consumption

Plant water requirement in plant root zone is given as

$$\mathbf{I + P - (D + ET) = \pm \Delta S}$$

where I, P, D, ET and ΔS represent irrigation, precipitation or rainfall, drainage, evapotranspiration, (Oyediran 1977, Kirda 1990, Lirbadi *et. al.,* 1996) and change in soil water storage of the plant root zone respectively. Change in soil water storage of the plant root zone (ΔS) is determined by using capacitance probe (*Diviner 2000*).

5.4 Soil Moisture Deficit and Available Water

The upper limit for water content represents the maximum water contents observed in a profile for a given hydrological setting. For a freely draining profile in the given hydrological setting, the upper limit [the field capacity (FC)] is 0.24 cm^3cm^{-3}. Whereas

the lower limit of water content can be established as the measurement following a long drying period i.e. the wilting point (WP) which is 0.10 cm^3cm^{-3} (Greacen, 1981).

The effective rooting depth of maize in this soil is 30 cm. Therefore, soil water storage at field capacity is

S(FC) = 0.24 x 30 = 7.2 cm/30 cm of soil

Soil water storage should be maintained at this level, if available soil water for plant growth, is to be kept at the level of 100%. Minimum soil water storage at wilting is

S(WP) = 0.10 x 30 = 3.0 cm/30 cm of soil

this conversely designates 0 % available water. The profile water stored which is the readily available water content (RAWC) which is the difference between the upper and the lower limits of water content to some specified depth, usually the root zone which is 30 cm for maize crop. That is

RAWC = S(FC) – S(WP)

= 7.2 – 3.0 = 4.2 cm/30 cm

5.4.1 Developmental stage

At developmental stages for plant growth, water intakes by the plant for three treatments considered in this case (Table 5.2) is proportionate to the growth of plant. That is, at this stage the plant water intake is not much and therefore there is enough water to all treatments.

Table 5.2: Water Content distribution for Maize 95 TYZEE-Y at Development stage

Treatment	Depth Z (cm)	Water contents at different dates 22/03/03	25/03/03	28/03/03
			θ (cm^3cm^{-3})	
T_1	10	0.158	0.110	0.115
	20	0.246	0.213	0.200
	30	0.308	0.291	0.300
T_4	10	0.123	0.089	0.111
	20	0.211	0.195	0.203
	30	0.277	0.273	0.273
T_6	10	0.100	0.121	0.087
	20	0.201	0.213	0.204
	30	0.215	0.221	0.221

5.4.1.1 Development stages T_1

The soil water storage on 22/03/03 is

S(cm/30 cm) = 10 x 0.158 + 10 x 0.246 + 10 x 0.308

= 7.12 cm/30 cm

Available water (AW) left in the soil is

AW = 7.12 - S(WP)

= 7.12 – 3.0 = 4.12 cm/30 cm

%AW = (AW/RAWC) x 100

= (4.12/4.2) x 100 = 98.10 %

This indicates that field has enough AW for plant. The field has just been irrigated.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 7.12 = 0.08 cm

The soil water storage on 25/03/03 is

S(cm/30 cm) = 10 x 0.110 + 10 x 0.213 + 10 x 0.291

= 6.14 cm/30 cm

Available water (AW) left in the soil is

AW = 6.14 - S(WP)

= 6.14 – 3.0 = 3.14 cm/30 cm

%AW = (AW/RAWC) x 100

= (3.14/4.2) x 100 = 74.76 %

This indicates that field has enough AW. There is AW for soil and therefore does not need irrigation yet.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 6.14 = 1.06 cm

The soil water storage on 28/03/03 is

S(cm/30 cm) = 10 x 0.115 + 10 x 0.200 + 10 x 0.300

= 6.15 cm/30 cm

Available water (AW) left in the soil is

AW = 6.15 - S(WP)

= 6.15 – 3.0 = 3.15 cm/30 cm

%AW = (AW/RAWC) x 100

= (3.15/4.2) x 100 = 75.00 %

This indicates that field has enough AW. There is AW for soil and therefore does not need irrigation yet.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 6.15 = 1.05 cm

5.4.1.2 Development stages T_4

The soil water storage on 22/03/03 is

S(cm/30 cm) = 10 x 0.123 + 10 x 0.211 + 10 x 0.277

= 6.11 cm/30 cm

Available water (AW) left in the soil is

AW = 6.11 - S(WP)

= 6.11 – 3.0 = 3.11 cm/30 cm

%AW = (AW/ RAWC) x 100

= (3.11/4.2) x 100 = 74.05 %

This indicates that field has enough AW for plant and therefore does not need irrigation yet. It has just been irrigated 2 days earlier.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 6.11 = 1.09 cm

The soil water storage on 25/03/03 is

S(cm/30 cm) = 10 x 0.089 + 10 x 0.195 + 10 x 0.273

= 5.57 cm/30 cm

Available water (AW) left in the soil is

AW = 5.57 - S(WP)

= 5.57 – 3.0 = 2.57 cm/30 cm

%AW = (AW/ RAWC) x 100

= (2.57/4.2) x 100 = 61.19 %

This indicates that field has enough AW for plant and therefore does not need irrigation yet.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 5.57 = 1.63 cm

The soil water storage on 28/03/03 is

S(cm/30 cm) = 10 x 0.111 + 10 x 0.206 + 10 x 0.271

= 5.88 cm/30 cm

Available water (AW) left in the soil is

AW = 5.88 - S(WP)

= 5.88 – 3.0 = 2.88 cm/30 cm

%AW = (AW/ RAWC) x 100

= (2.88/4.2) x 100 = 68.57 %

This indicates that field has enough AW for plant and therefore does not need irrigation yet.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 5.88 = 1.32 cm

5.4.1.3 Development or Vegetative stages T_6

The soil water storage on 22/03/03 is

S(cm/30 cm) = 10 x 0.100+ 10 x 0.201+ 10 x 0.215

= 5.16 cm/30 cm

Available water (AW) left in the soil is

AW = 5.16 - S(WP)

= 5.16 – 3.0 = 2.16 cm/30 cm

%AW = (AW/RAWC) x 100

= (2.16/4.2) x 100 = 51.43 %

This indicates that the AW in the field is just above permissible level, and therefore field has to be irrigated.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 5.16 = 2.04 cm

The soil water storage on 25/03/03 is

S(cm/30 cm) = 10 x 0.121+ 10 x 0.213+ 10 x 0.221

= 5.55 cm/30 cm

Available water (AW) left in the soil is

AW = 5.55 - S(WP)

= 5.55 – 3.0 = 2.55 cm/30 cm

%AW = (AW/ RAWC) x 100

= (2.55 /4.2) x 100 = 60.71 %

This indicates that the AW in the field is above permissible level, and therefore does not need irrigation yet.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 5.55 = 1.65 cm

The soil water storage on 28/03/03 is

S(cm/30 cm) = 10 x 0.087+ 10 x 0.204+ 10 x 0.221

= 5.12 cm/30 cm

Available water (AW) left in the soil is

AW = 5.12- S(WP)

= 5.12 – 3.0 = 2.12 cm/30 cm

%AW = (AW/ RAWC) x 100

= (2.12 /4.2) x 100 = 50.48 %

This indicates that the AW in the field is just above permissible level, and therefore field has to be irrigated.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 5.12 = 2.08 cm

5.4.2 Establishment stages

Table 5.3: Water Content distribution for Maize 95 TYZEE-Y at Establishment stage

Treatment	Depth Z (cm)	Water contents at different dates 23/04/03	26/04/03	29/04/03
		θ (cm^3cm^{-3})		
T_1	10	0.120	0.077	0.064
	20	0.142	0.100	0.081
	30	0.174	0.176	0.170
T_4	10	0.038	0.062	0.028
	20	0.141	0.147	0.114
	30	0.239	0.229	0.215
T_6	10	0.092	0.040	0.027
	20	0.106	0.099	0.093
	30	0.235	0.223	0.217

5.4.2.1 Establishment stage T_1

The soil water storage on 23/04/03 is

S(cm/30 cm) = 10 x 0.120+ 10 x 0.142+ 10 x 0.174

= 4.36 cm/30 cm

Available water (AW) left in the soil is

AW = 4.36 - S(WP)

= 4.36 – 3.0 = 1.36 cm/30 cm

%AW = (AW/TAW) x 100

= (1.36/4.2) x 100 = 32.38 %

This indicates that AW decreased below permissible level, and therefore the field has to be irrigated.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

$$I = S(FC) - S$$

$$= 7.2 - 4.36 = 2.84 \text{ cm}$$

The soil water storage on 26/04/03 is

$$S(\text{cm}/30 \text{ cm}) = 10 \times 0.077 + 10 \times 0.100 + 10 \times 0.176$$

$$= 3.53 \text{ cm}/30 \text{ cm}$$

Available water (AW) left in the soil is

$$AW = 3.53 - S(WP)$$

$$= 3.53 - 3.0 = 0.53 \text{ cm}/30 \text{ cm}$$

$$\%AW = (AW/TAW) \times 100$$

$$= (0.53 / 4.2) \times 100 = 12.62 \%$$

This indicates that AW decreased below permissible level, and therefore the field has to be irrigated before it reaches onset of crop stress.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

$$I = S(FC) - S$$

$$= 7.2 - 3.53 = 3.67 \text{ cm}$$

The soil water storage on 29/04/03 is

$$S(\text{cm}/30 \text{ cm}) = 10 \times 0.064 + 10 \times 0.081 + 10 \times 0.170$$

$$= 3.57 \text{ cm}/30 \text{ cm}$$

Available water (AW) left in the soil is

AW = 3.15 - S(WP)

= 3.15 – 3.0 = 0.15 cm/30 cm

%AW = (AW/TAW) x 100

= (0.15/4.2) x 100 = 3.57 %

This indicates that AW decreased below permissible level, and therefore the field has to be irrigated. This also indicates the onset of crop stress.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 3.15 = 4.05 cm

5.4.2.2 Establishment stage T_4

The soil water storage on 23/04/03 is

S(cm/30 cm) = 10 x 0.038 + 10 x 0.141 + 10 x 0.239

= 4.18 cm/30 cm

Available water (AW) left in the soil is

AW = 4.18 - S(WP)

= 4.18 – 3.0 = 1.18 cm/30 cm

%AW = (AW/TAW) x 100

= (1.18/4.2) x 100 = 28.10 %

This indicates that AW decreased below permissible level, and therefore the field has to be irrigated.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

$$I = S(FC) - S$$

$$= 7.2 - 4.18 = 3.02 \text{ cm}$$

The soil water storage on 26/04/03 is

$$S(\text{cm}/30 \text{ cm}) = 10 \times 0.062 + 10 \times 0.147 + 10 \times 0.228$$

$$= 4.37 \text{ cm}/30 \text{ cm}$$

Available water (AW) left in the soil is

$$AW = 4.37 - S(WP)$$

$$= 4.37 - 3.0 = 1.37 \text{ cm}/30 \text{ cm}$$

$$\%AW = (AW/TAW) \times 100$$

$$= (1.37/4.2) \times 100 = 32.62 \%$$

This indicates that AW decreased below permissible level, and therefore the field has to be irrigated.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

$$I = S(FC) - S$$

$$= 7.2 - 4.37 = 2.83 \text{ cm}$$

The soil water storage on 29/04/03 is

$$S(\text{cm}/30 \text{ cm}) = 10 \times 0.028 + 10 \times 0.114 + 10 \times 0.215$$

$$= 3.57 \text{ cm}/30 \text{ cm}$$

Available water (AW) left in the soil is

$$AW = 3.57 - S(WP)$$

= 3.57 – 3.0 = 0.57 cm/30 cm

%AW = (AW/TAW) x 100

= (0.57/4.2) x 100 = 13.57 %

This indicates that AW decreased below permissible level, and therefore the field has to be irrigated. This also indicates the onset of crop stress.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

I = S(FC) - S

= 7.2 - 3.57 = 3.63 cm

5.4.2.3 Establishment stage T_6

The soil water storage on 23/04/03

S(cm/30 cm) = 10 x 0.092 + 10 x 0.106 + 10 x 0.235

= 4.33

Available water (AW) left in the soil is

AW = 4.33 - S(WP)

= 4.33 – 3.0 = 1.33 cm/30 cm

%AW = (AW/TAW) x 100

= (1.33/4.2) x 100 = 31.67 %

which indicates that AW decreased below permissible level, and therefore their is onset of crop stress, and no amount of irrigation can revive the crops again.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

$$I = S(FC) - S$$

$$= 7.2 - 4.33 = 2.87 \text{ cm}$$

The soil water storage on 26/04/03

$$S(\text{cm}/30 \text{ cm}) = 10 \times 0.040 + 10 \times 0.099 + 10 \times 0.223$$

$$= 3.62$$

Available water (AW) left in the soil is

$$AW = 3.62 - S(WP)$$

$$= 3.62 - 3.0 = 0.62 \text{ cm}/30 \text{ cm}$$

$$\%AW = (AW/TAW) \times 100$$

$$= (0.62/4.2) \times 100 = 14.76 \%$$

which indicates that AW decreased below permissible level, and therefore their is onset of crop stress, and no amount of irrigation can revive the crops again.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

$$I = S(FC) - S$$

$$= 7.2 - 3.62 = 3.58 \text{ cm}$$

The soil water storage on 29/04/03

$$S(\text{cm}/30 \text{ cm}) = 10 \times 0.027 + 10 \times 0.093 + 10 \times 0.217$$

$$= 3.37$$

Available water (AW) left in the soil is

$$AW = 3.37 - S(WP)$$

$$= 3.37 - 3.0 = 0.37 \text{ cm}/30 \text{ cm}$$

$$\%AW = (AW/TAW) \times 100$$

$$= (0.37/4.2) \times 100 = 8.81 \%$$

which indicates that AW decreased below permissible level, and therefore their is onset of crop stress, and no amount of irrigation can revive the crops again.

The net amount of irrigation water needed to bring the AW to 100 % level is simply the difference between soil water storage, prior to irrigation, and storage at field capacity S(FC):

$$I = S(FC) - S$$

$$= 7.2 - 3.37 = 3.83 \text{ cm}$$

Table 5.4 % Available Water for Maize 95 TYZEE-Y at Development stage

Treatments	Dates	Soil water storage	Available water (AW)	% Available water (%AW)	Irrigation
T_1	22/03/03	7.12	4.12	98.10	0.08
	25/03/03	6.14	3.14	74.76	1.06
	28/03/03	6.15	3.15	75.00	1.05
T_4	22/03/03	6.11	3.11	74.05	1.09
	25/03/03	5.57	2.57	61.19	1.63
	28/03/03	5.88	2.88	68.57	1.32
T_6	22/03/03	5.16	2.16	51.43	2.04
	25/03/03	5.55	2.55	60.71	1.65
	28/03/03	5.12	2.12	50.48	2.08

Table 5.5 % Available Water for Maize 95 TYZEE-Y at Establishment Stages

Treatments	Dates	Soil water storage	Available water (AW)	% Available water (%AW)	Irrigation
T_1	23/04/03	4.36	1.36	32.38	2.84
	26/04/04	3.53	0.53	12.62	3.67
	29/04/04	3.15	0.15	3.57	4.05
T_4	23/04/03	4.18	1.18	28.10	3.02
	26/04/04	4.37	1.37	32.62	2.83
	29/04/04	3.57	0.57	13.57	3.63
T_6	23/04/03	4.33	1.33	31.67	2.87
	26/04/04	3.62	0.62	14.76	3.58
	29/04/04	3.37	0.37	8.81	3.83

5.4.3 Discussion

At development stage the amount of soil water storage available for plant at irrigation days continues to reduce as plant grow. Crop water requirements vary with stage of growth. The water intake by plant after ponding has similar pattern in all stages. For treatment 6, on the 6^{th} day after ponding, about 70% of water available for plant has been used and plant begin to have water stress.

These patterns fits the company Sentek Pty Ltd on soil water dynamics in the crop root zone as shown in figure 5.5; there are three stages/phases in crop water supply and uses:

Phase 1: Soil water is still draining and therefore soil water is available for crop use.

Phase 2: Soil water has finished draining, and therefore soil is saturated and soil water is still available for crop use.

Phase 3: Indicate that there is decline in soil water which results to onset of crop water stress and therefore soil water is not readily available, crop yield and quality is impaired.

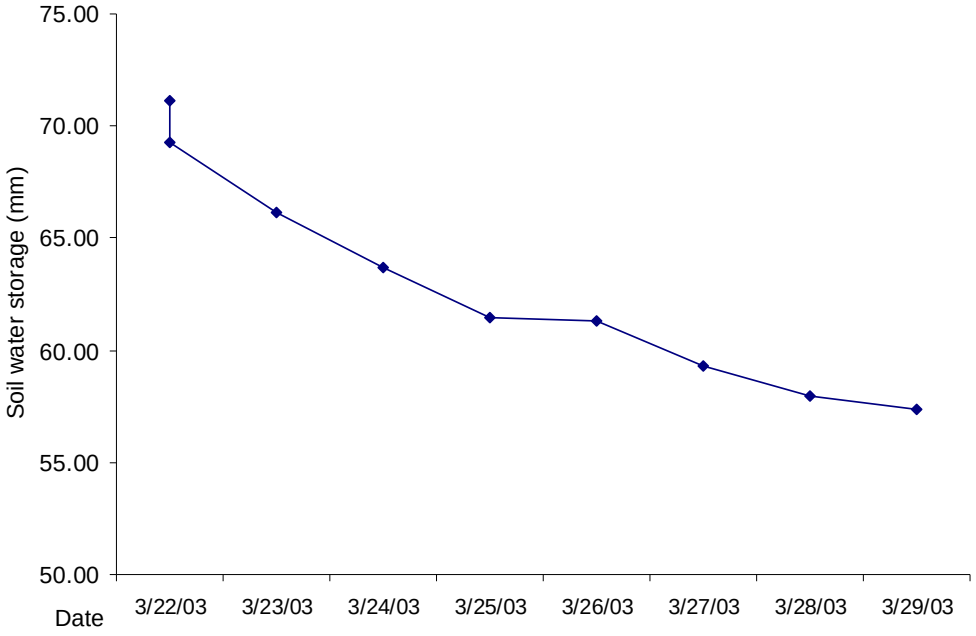

Fig. 5.3a Soil water dynamics in the root zone for T_6 at development stage

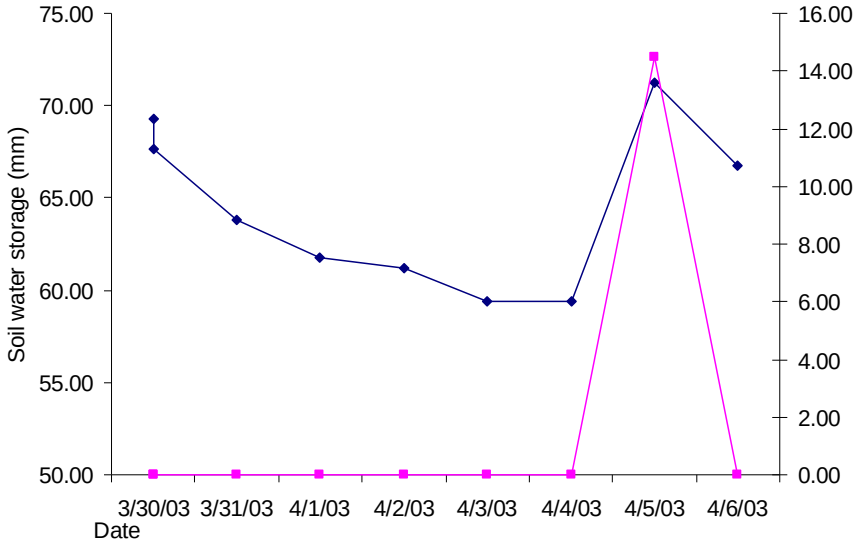

Fig. 5.3b Soil water dynamics in the root zone for T_6 at development stage

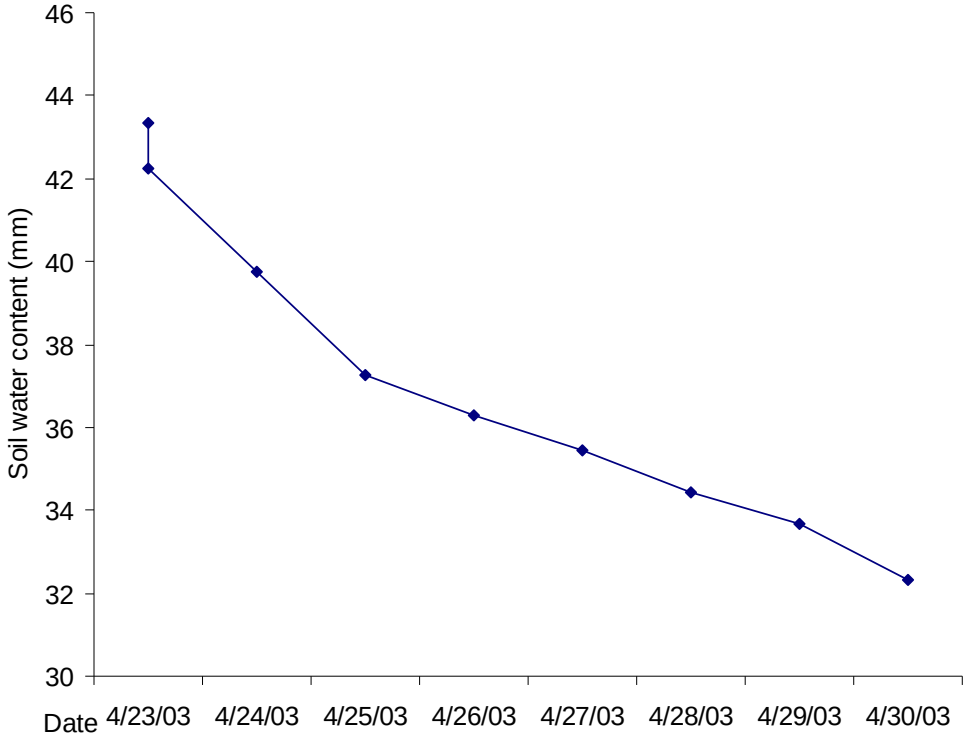

Fig.5.4a Soil water dynamics at root zone for T_6 at establishment stage

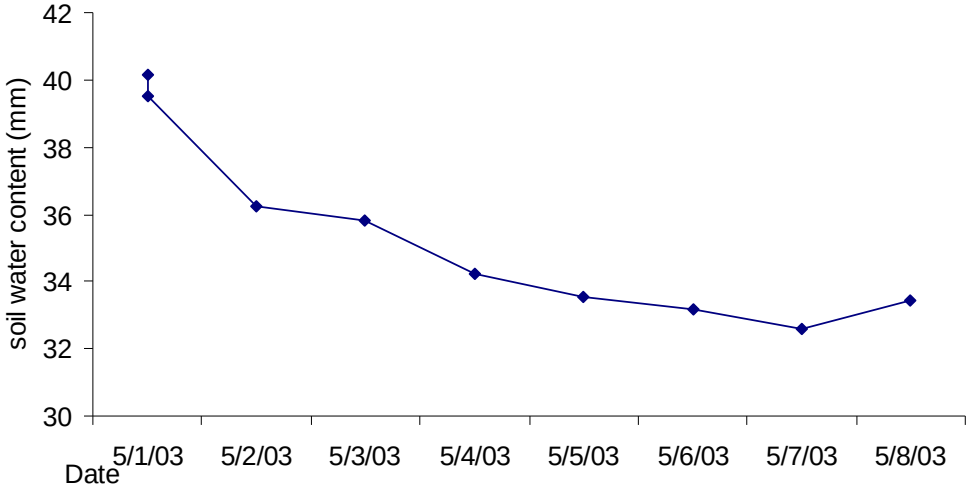

Fig.5.4b Soil water dynamics at root zone for T_6 at establishment stage

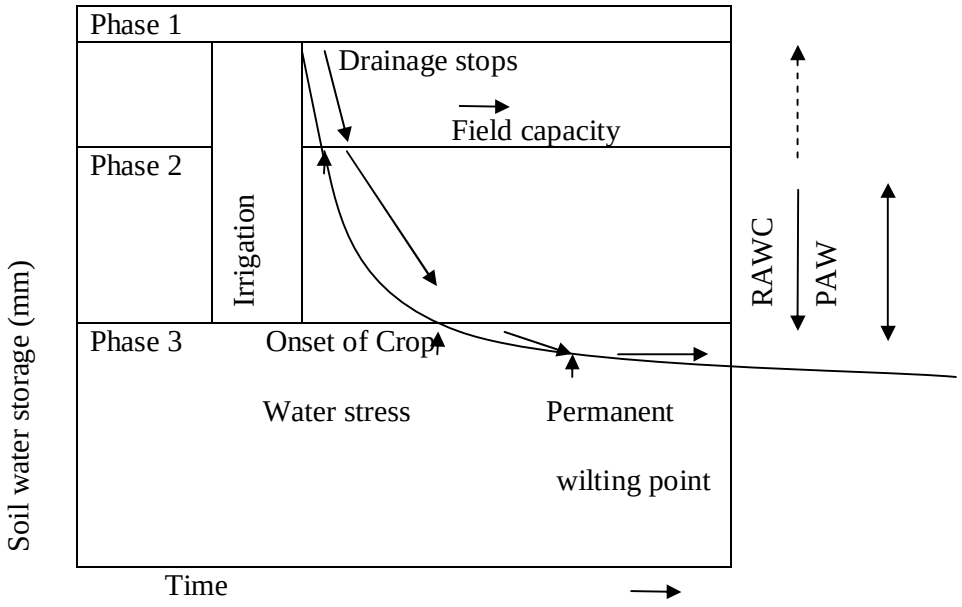

Figure 5.5 Soil water dynamics in the crop root zone (Adopted from Sentek Pty Ltd).

5.4.3.1 Important Terms in Plant Water Consumption

Amount of water left in root zone of crops is called the **field capacity**. It is the moisture content after drainage of gravitational water and is the upper limit of moisture held in

soils by capillarity. This is most important in adjusting the refill amount for a particular type and depth of root zone in order to prevent over irrigation.

Plant Available Water (PAW) describes the amount of water extracted by a crop between field capacity and permanent wilting point. **Permanent wilting point** is the soil moisture content at which the crop is subjected to irreversible wilting.

PAW = S(FC) - S(WP)

Readily available Water Capacity (RAWC) is preferred for use in irrigation scheduling because it's defined as lower limit (onset of crop water stress) and is an exact irrigation trigger index of the crop that signals onset of water stress from a crop's point of view.

Onset of crop water stress is the soil moisture content in plant root zone when first observable slow down of maximum daily crop water use rate after irrigation or rainfall occurs. This slow down should not be caused by a change in weather conditions, phenological stage of the crop, crop disease, harvest, spraying with chemicals or insect damage. These factors need to be excluded through crop observation and weather monitoring. In other words, a slow down in soil water change after a cool weather change is only a temporary matter that does not necessarily mean the onset of water stress. Slow down of daily soil water changes should correlate only with the starting difficulties of the plant to develop sufficient osmotic pressure to extract soil water from a diminishing soil water reservoir. Crop water requirements vary with stage of growth. Long term monitoring of plant physiological parameters will improve the accuracy with which refill point is determined for different crop growth stage.

Full point is the moisture content after an irrigation, it replaces the amount of soil water extraction at bottom of crop root zone, at the same magnitude as it was removed by the

plant. The key point is that soil moisture content replenishment in the plant root zone should not produce a significant drainage change below bottom of the root zone, wasting water and fertilizer.

Drought stress at beginning of the season severely affect plant establishment and at the seedling and flowering stages of maize (*Zea mays L.*) it is estimated to cause annual yield loss of about 12% in the West African sub-region (Kamara *et al.*, 2001).

5.5 Soil water balance

Soil water balance, is an account of all quantities of water added, removed or stored in a given volume of soil during a given period of time. The soil water balance equation thus helps in making estimates of parameters, which influence the amount of soil water. Amount of water in a soil layer is determined by those factors that add water to the soil and those factors that remove water from it. Hence soil water balance equation in its simplest form of expression is:

Change in soil water = Inputs of water - Losses of water

Water is usually added to the soil in three measurable ways - precipitation (P), irrigation (I), and contribution from ground-water table (C). Contribution from the ground water will be significant only if the ground-water table is near the surface.

So, the inputs of water can be presented as:

Water Inputs = P + I + C

Water is removed from soil through evaporation from soil surface or transpiration through plant together known as evapotranspiration (ET), and deep drainage (D). Further, part of the rain water received at soil surface may be lost as surface runoff (RO).

The above three factors are negative factors in the equation. The losses of water from soil can then be represented by the following equation.

Water Losses = ET + D + RO

Change in the soil water content which is the difference between water added and water withdrawn will now read:

Change in Soil water (ΔS) = (P + I + C) - (ET + D + RO)

Soil water refers to the amount of water held in root zone of crop at a given time. This amount can be measured. The change in soil water from one measurement to another depends on contribution of components in the equation. In this situation the contribution from ground water table is zero so also the surfaces run off.

$$\mathbf{I + P - (D + ET) = \pm \Delta S} \qquad 5.1$$

where I, P, D, ET and ΔS represent irrigation, rainfall, drainage, evapotranspiration, and change in soil water storage of the plant root zone respectively(Oyediran, 1977; Kirda 1990; Lirbadi *et al.*, 1996). Change in soil water storage of the plant root zone (ΔS) is determined by using soil moisture measurement techniques such as neutron moisture gauge, capacitance probe, time domain reflectometre, etc.

In this experiment capacitance probe (*Diviner 2000*) was used. This is determined by knowing the changes of water storage in the plant root zone before and after irrigation. Only soil water content distribution profiles within the plant root zone are needed to calculate the amount of soil water stored (S(t)). This is assessed by capacitance probe as

$$S(t) = \int_0^L \theta dz \qquad 5.2$$
$$S(t) = \Sigma \theta \Delta z$$

where the right hand sides of the equations [5.2] above are the area under the soil water profile curve.

Under rain fed agricultural system in arid and semiarid regions, it is assumed that during certain periods of plant growing season

$$I = 0; \quad P = 0; \quad D = 0;$$

In this case, plant water consumption (i.e. evapotranspiration) is simply

$$\mathbf{ET = -\Delta S} \qquad 5.3$$

However, the case in question is not rain fed, therefore

$$I \neq 0; \quad P \neq 0; \quad D = 0;$$

In this case, plant water consumption is simply

$$\mathbf{I + P = ET \pm \Delta S} \qquad 5.4$$

Fig. 5.6: Soil Water balance for Maize in three seasons.

Treatment	Seasons											
	2003				2004				2005			
	I (mm)	P (mm)	ET (mm)	ΔS (mm)	I (mm)	P (mm)	ET (mm)	ΔS (mm)	I (mm)	P (mm)	ET (mm)	ΔS (mm)
T_1	616	63.4	684.09	-4.69	616	121.3	750.48	-13.18	616	176	801.86	-9.86
T_2	462	63.4	526.85	-1.45	462	121.3	597.30	-14.00	462	176	648.44	-10.44
T_3	369	63.4	427.93	4.47	369	121.3	498.06	-7.76	369	176	552.99	-7.99
T_4	308	63.4	371.27	0.13	308	121.3	442.65	-13.35	308	176	482.87	1.13
T_5	264	63.4	323.07	4.33	264	121.3	391.97	-6.67	264	176	436.89	3.11
T_6	231	63.4	292.86	1.54	231	121.3	345.74	6.56	231	176	401.01	5.99

5.6 Agronomic Data

5.6.1 Plant Height and Stem Girth

Plant analysis at early vegetative stages of growth in their height and stem is not significantly difference from each other for all treatments (see appendix B1 and B2). The analysis of variance (ANOVA) shows that F (= 0.38758) is less than F crit (=2.77285), which suggest that there is no difference in water treatment given to the plant in all the treatment. In this case the amount of water needed by the plant is not much. We can therefore minimize water by choosing treatment 5 or 6, after proper fertilizer placement in the first four week. This could be observed through the figures of the height and stem in the early vegetative stage of the plant. However, plant analysis at the reproductive stage in their height and stem differ significantly from each other in all the treatments. The analysis of the variance (ANOVA) shows that the F (= 9.283995) is greater than F crit (=2.77285), which suggest that there is significant difference in water treatment given to the plant. And these provide valuable information on the amount of water needed at reproductive or establishment stages. At this stage of the plant growth it is advisable to revert to treatment 1 or 2 for better yield.

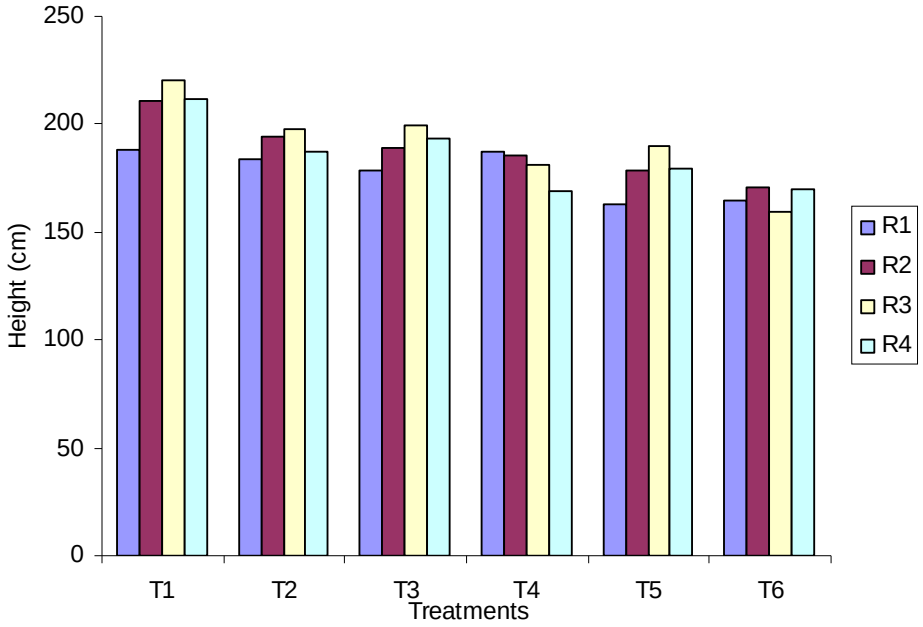

Fig. 5.6: Height of Maize Plant 95 TZEE-Y on 07/05/04

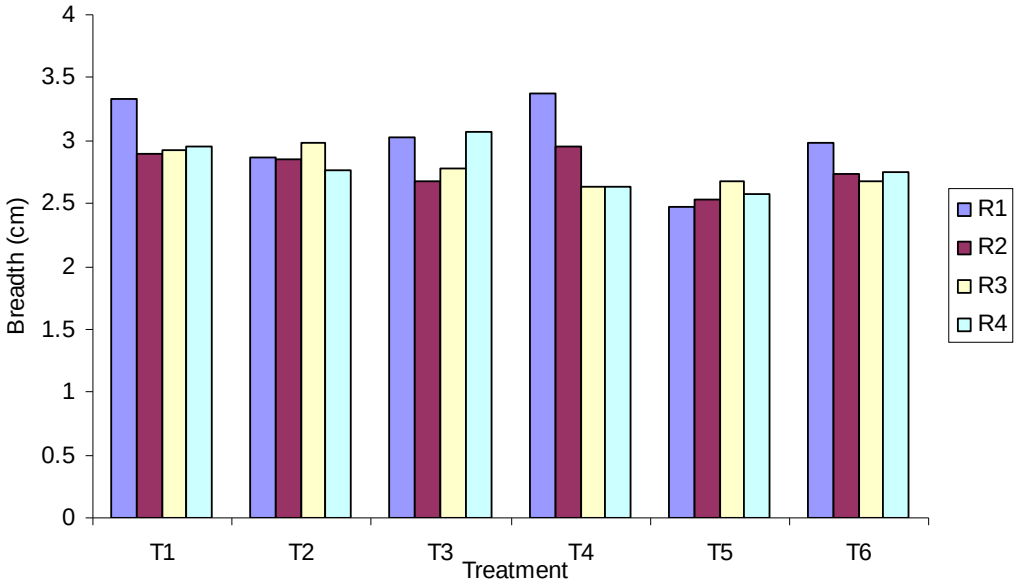

Fig. 5.7: Stem of Maize Plant 95 TZEE-Y on 07/05/04

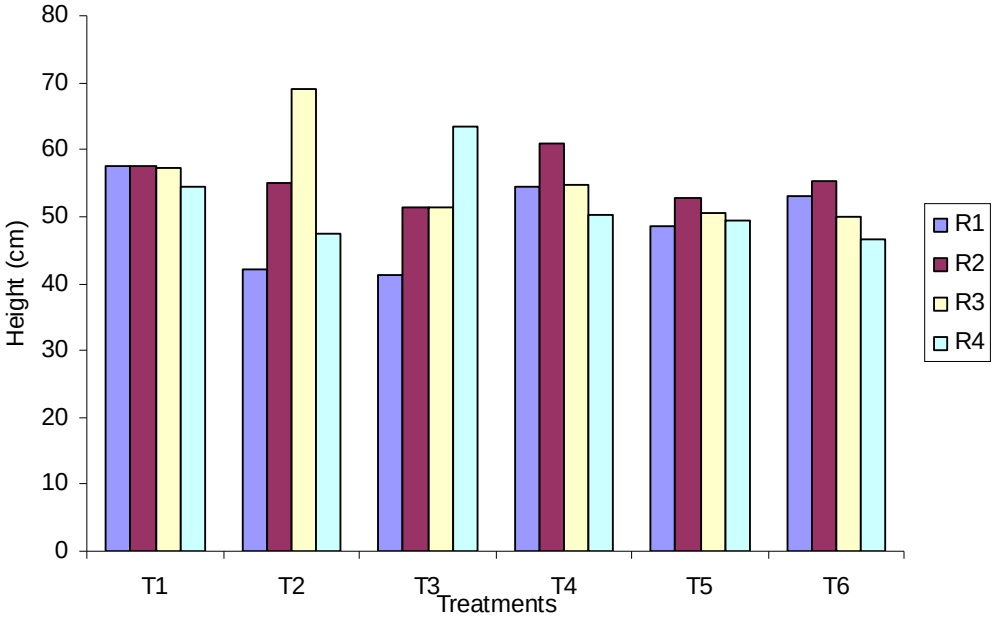

Fig. 5.8: Height of Maize plant 95 TZEE-Y on 11/04/04

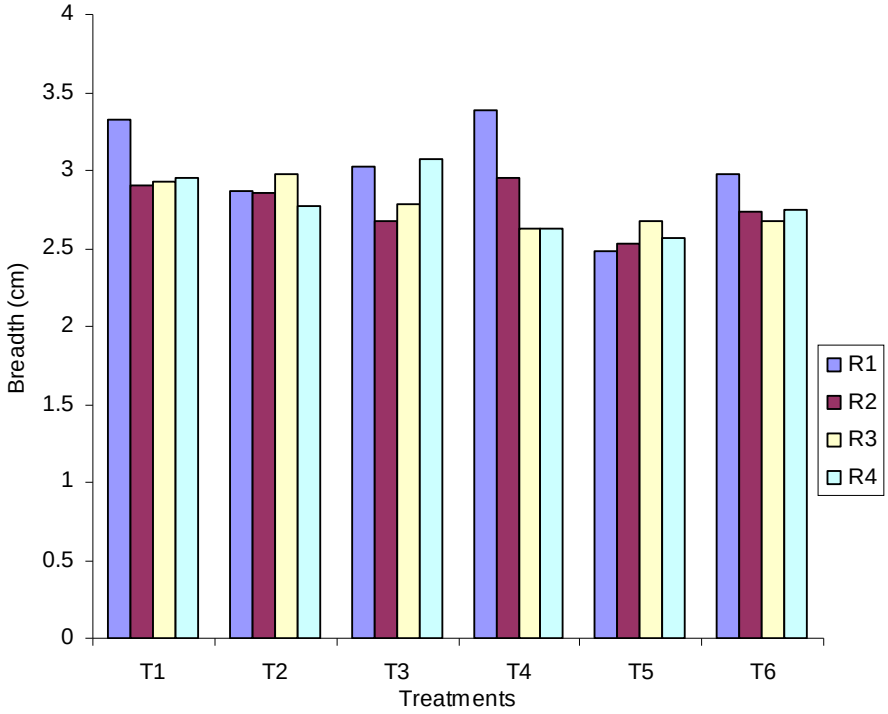

Fig. 5.9: Stem of Maize Plant 95 TZEE-Y on 11/04/04

5.7 Water Use Efficiency

In arid and semiarid regions, water resources are scarce and therefore critical for irrigation purposes, and consequently dry season farming practices are commonly used. Crop cultivars with high water use efficiency (WUE) have prime importance for optimum use of available water resources. Therefore, maize (95 TZEE-Y) crop variety with high WUE is of immediate practical application. The estimation of WUE for a crop is the water consumption during the growing season, which is measured by the capacitance or neutron probe (see Table 5.7, 5.8 and 5.9). WUE is calculated as follow

WUE = Yield/Water consumption

The yield can be expressed in various ways, depending on interests of the farmers. It is observed that in this area, in which the research is purposely made, only grain is important though other crop residue can equally be available as animal feed.

Therefore, the yield (Y) is better expressed as the above –ground dry matter and thus ignoring the root system (Kirda, 1990). Total water used at field level (U) can be partitioned into its respective components as

$$U = E + T + R + D \qquad 5.5$$

Where E is evaporation from soil surface, T is transpiration, R is runoff and D is the water lost through deep percolation. However, it is difficult to apportion water use into that lost by transpiration and that lost by soil evaporation, and therefore their combination is referred to as evapotranspiration (ET). Therefore

$$WUE = \frac{Y}{U} \qquad 5.6$$

$$WUE = \frac{Y/T}{1 + (E + R + D)/T} \qquad 5.7$$

where the ratio Y/T is called transpiration efficiency. There are three ways to increase WUE (Copper *et al.*, 1987). They are:

1. changing transpiration efficiency (Y/T);
2. increasing T by way of increasing total water supply at field level; and
3. if the supply of water is limited, reducing water loss through pathways other than transpiration.

The WUE figures 5.10, 5.11 and 5.12 are similar in output and regression analysis. The standard error is between 0.562 and 0.440 and has no significant difference (see appendix F) from there analysis of variance.

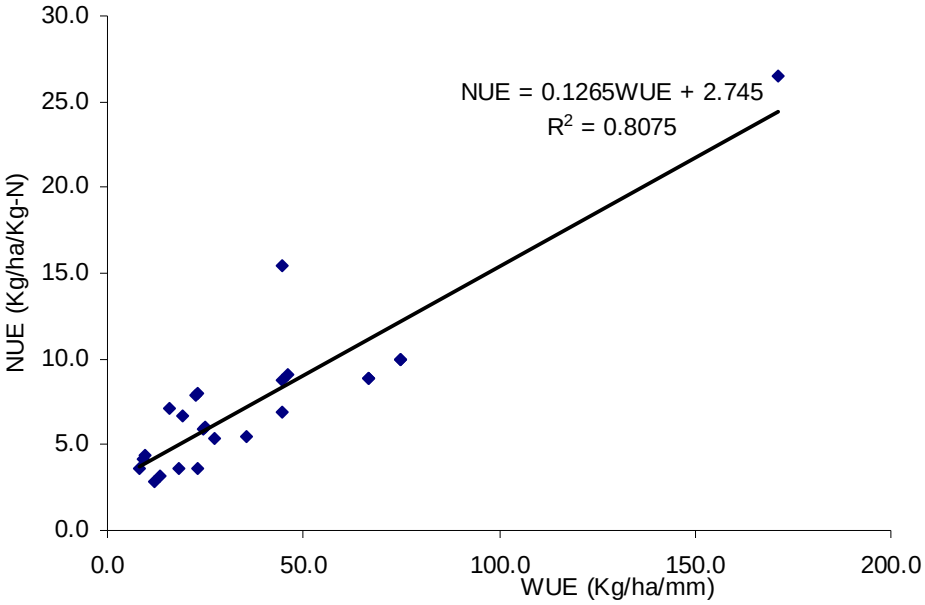

Fig. 5.10 Water Use Efficiency for irrigation in 2003

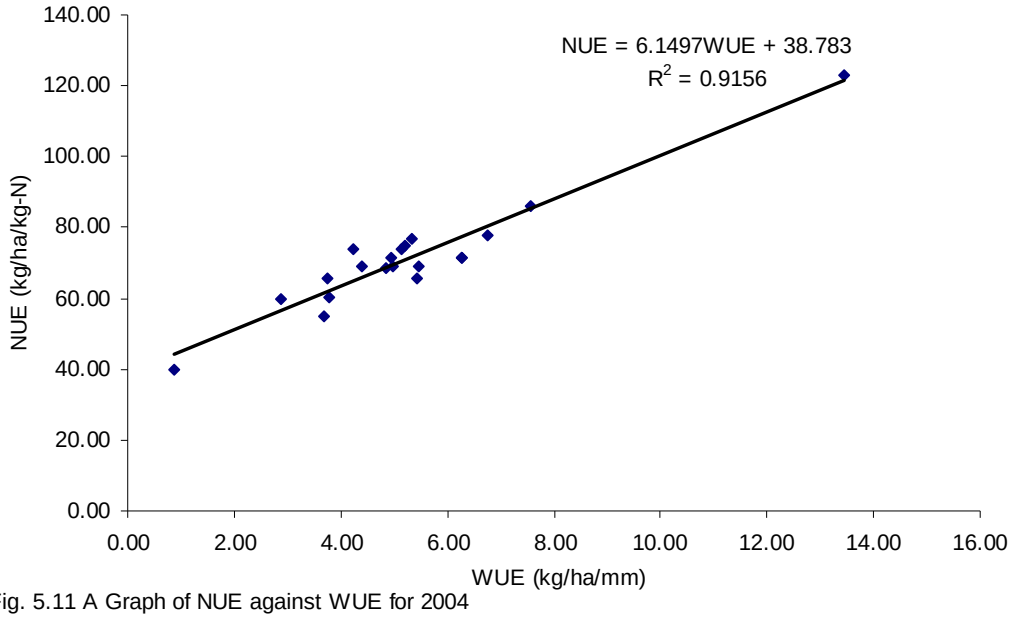

Fig. 5.11 A Graph of NUE against WUE for 2004

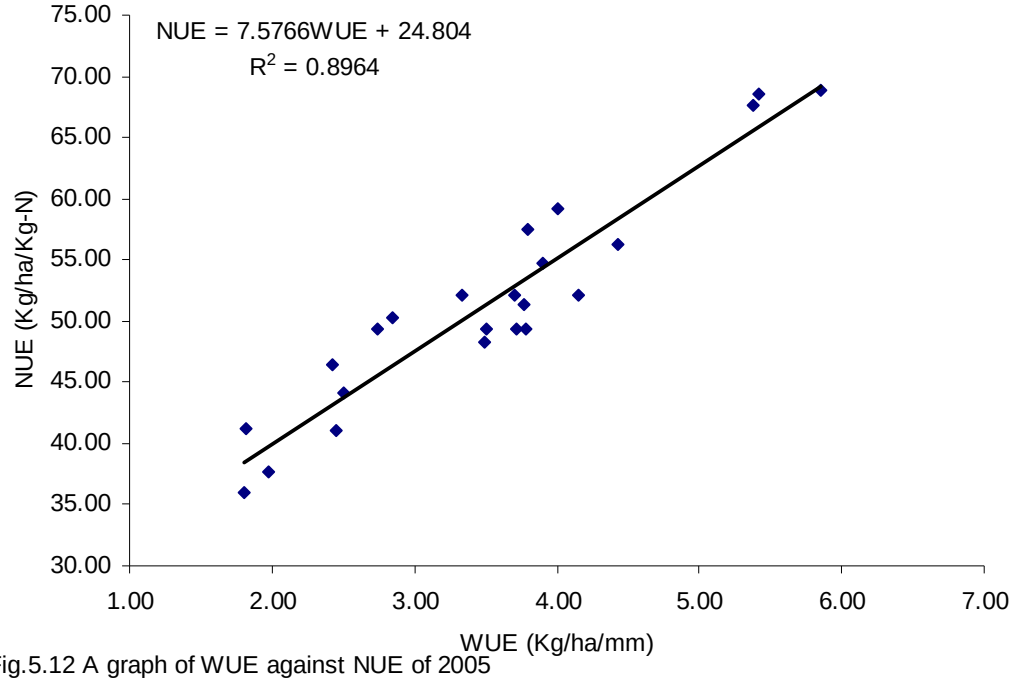

Fig.5.12 A graph of WUE against NUE of 2005

Table 5.7: Water use efficiency and Grain yield in 2003

Treatment	Total water used (mm)	Grain yield (Kg/ha)	Water use efficiency (Kg/ha.mm)	Nitrogen use efficiency (Kg/ha)
T_1	683.75	2800	4.10	76.71
	656.96	3000	4.57	82.19
	655.55	2750	4.19	75.34
	655.55	2300	3.51	63.01
T_2	504.53	1800	3.57	49.32
	509.58	2000	3.92	54.79
	503.85	2100	4.17	57.53
	505.30	2000	3.96	54.79
T_3	414.90	2400	5.78	65.75
	415.15	2000	4.82	54.79
	414.09	2500	6.04	68.49
	414.09	2000	4.83	54.79
T_4	352.60	2150	6.10	58.90
	350.67	2000	5.70	54.79
	315.57	1760	5.01	48.22
	351.57	1770	5.03	48.49
T_5	312.36	2200	7.04	60.27
	310.00	1840	5.94	50.41
	308.41	1770	5.74	48.49
	309.26	1570	5.08	43.01
T_6	279.52	1660	5.94	45.48
	275.09	1680	6.11	46.03
	276.39	1680	6.08	46.03
	276.39	1660	6.01	45.48

Table 5.8: Water use efficiency and Grain yield in 2004

Treatment	Total water used (mm)	Grain yield (Kg/ha)	Water use efficiency (Kg/ha.mm)	Nitrogen use efficiency (Kg/ha)
T_1	731.33	2400	3.28	65.75
	721.63	2500	3.46	68.49
	719.41	2500	3.48	68.49
	731.33	2000	2.73	54.79
T_2	574.59	2400	4.18	65.75
	562.58	2400	4.27	65.75
	570.74	2700	4.73	73.97
	638.48	2800	4.39	76.71
T_3	482.11	2800	5.81	76.71
	485.32	2700	5.56	73.97
	481.98	2600	5.39	71.23
	481.98	2000	4.84	54.79
T_4	413.46	2000	4.84	54.79
	416.54	2400	5.76	65.75
	407.85	2900	7.11	79.45
	407.85	2200	5.39	60.27
T_5	383.38	2200	5.74	60.27
	379.95	2200	5.79	60.27
	372.53	2600	5.91	57.53
	372.53	2600	5.91	54.79
T_6	357.41	2100	5.91	57.53
	355.15	2000	5.51	54.79
	363.03	2500	6.99	68.49
	357.41	2500	6.99	68.49

Table 5.9: Water use efficiency and Grain yield in 2005

Treatment	Total water used (mm)	Grain yield (Kg/ha)	Water use efficiency (Kg/ha.mm)	Nitrogen use efficiency (Kg/ha)
T_1	779.26	1800	2.31	49.32
	784.48	1600	2.04	43.84
	782.68	2900	3.71	79.45
	782.68	2200	2.81	60.27
T_2	611.17	2100	3.44	57.53
	623.46	2100	3.37	57.53
	633.97	1800	2.84	49.32
	633.97	2100	3.31	57.53
T_3	540.88	2300	4.25	63.01
	536.53	2200	4.10	60.27
	535.43	2500	4.67	68.49
	535.43	1900	3.55	52.05
T_4	485.56	2000	4.12	54.79
	484.95	1800	3.71	49.32
	484.89	2500	5.16	68.49
	484.89	1900	3.92	52.05
T_5	438.51	1900	4.33	52.05
	438.89	1500	3.42	41.10
	451.94	1600	3.54	43.84
	451.94	1300	2.88	35.62
T_6	418.92	1800	4.30	49.32
	410.12	1900	4.63	52.05
	409.88	1700	4.15	46.58
	409.88	1200	2.93	32.88

5.8 Hydraulic conductivity

Soil hydraulic conductivity (K) and water content (θ) are key parameters for crop growth, irrigation, drainage, and modeling water flow and chemical transport through the soil. Using Libardi *et al.* (1980), Kirda (1990), Jones and Wagenet (1984) approaches to the measurement of soil hydraulic conductivity (K) and volumetric water content (θ) in the field as

$$K(\theta) = K_o \exp[\beta(\theta_o - \theta)] \qquad (5.8)$$

in which the table 5.10 is generated.

Table 5.10: Basic data for estimation of $K_o(z = 30cm, \theta_o = 84.03) and K(\theta)$

Time (t) (h)	Vol. water contents (θ) cm^3cm^{-3}	Diff. in vol. water contents $(\theta_o - \theta)$ cm^3cm^{-3}	$\ln[z(d\theta/dt)]$ cmh^{-1}	$K(\theta) = 2.64e^{-0.2856(\theta_o - \theta)}$ cmh^{-1}
0	84.03	0	-	-
6	82.43	1.6	3.076	1.672
24	80.95	3.08	1.612	1.096
30	80.47	3.56	1.376	0.956
48	77.06	6.97	0.88	0.361
54	78.15	5.88	0.755	0.493
72	77.71	6.32	0.452	0.434
78	76.95	7.08	0.367	0.349
96	75.78	8.25	0.148	0.250
102	76.69	7.34	0.084	0.325
120	73.81	10.22	-0.09	0.143
126	74.14	9.89	-0.14	0.157
144	72.64	11.39	-0.28	0.102
150	74.31	9.72	-0.32	0.165
168	72.13	11.9	-0.44	0.088

The data in Table 5.10 are enough to estimate unsaturated hydraulic conductivity which is assumed to be adequately described by equation [5.8] and also gives the major steps involved in the calculations. The slope $d\theta/dt$ is calculated using an exponential curve fitted for the pot of volumetric water content (θ) versus time (t) as shown in figure 5.13.

$$\theta = 85.533t^{-0.056}$$

$$\frac{d\theta}{dt} = -4.79t^{-1.056}, \quad \text{and} \quad r = 0.955$$

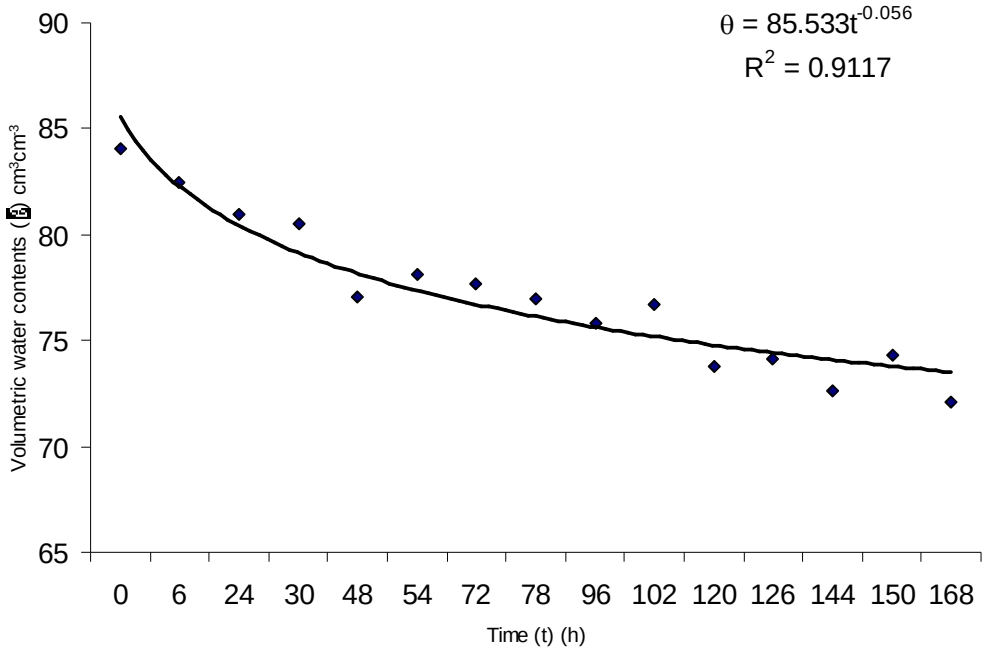

Fig.5.13: Decrease of mean soil water content (θ) with time (t)

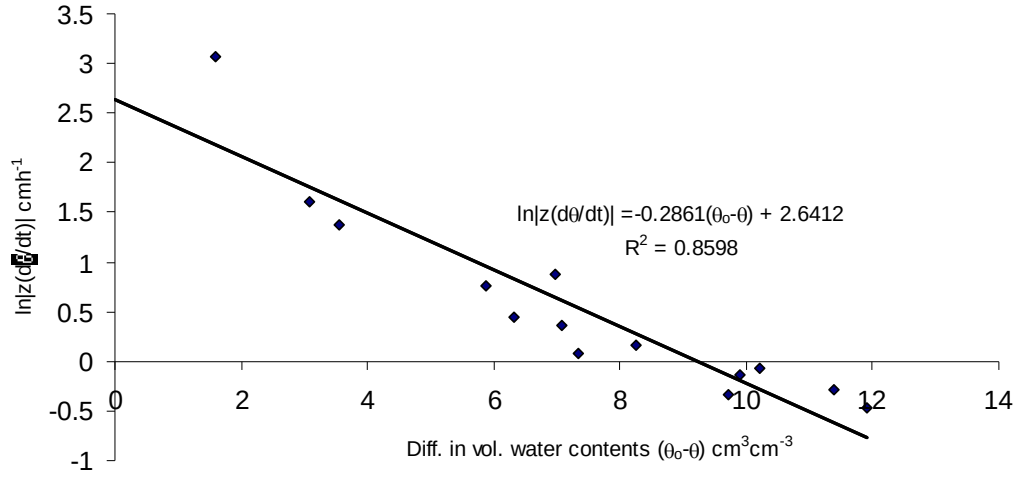

Fig. 5.14: Semi log plot of ln[z(dθ/dt)] vs (θ_o-θ)

The values of β and K_o are to be calculated using the field data and the relation

$$\ln\left[z\left(d\theta/dt\right)\right] = \beta\left(\theta_o - \theta\right) + \ln K_o \qquad 5.9$$

a semi-log plot of the absolute value of $\ln|z(d\theta/dt)|$ against $(\theta_o - \theta)$ gives β and $\ln K_0$ from the slope and intercept, respectively (Libardi *et al.*, 1980). In which the above equation takes the form

$$\ln\left[z\left(d\theta/dt\right)\right] = -0.2856\left(\theta_o - \theta\right) + 2.6393, \quad r = 0.927$$

Therefore, the exponential equation describing unsaturated hydraulic conductivity is given as

$$K\left(\theta\right) = 2.64\exp\left[-0.2856\left(84.03 - \theta\right)\right]$$

5.8.1 Discussion on Hydraulic conductivity

Estimation of hydraulic conductivity is essential for the determination of soil water fluxes and hence e.g. water balance in soil profile (Vose, 1980). Accurate soil water content measurements are required for measurements of crop water use and of hydraulic characteristics of soils. Soil hydraulic conductivity (K) and water content (θ) are key parameters for crop growth, irrigation, drainage, and modeling water flow and chemical transport through soil.

Among approaches to measurement of soil hydraulic conductivity (K) that is related to volumetric water content (θ) in the field is that of Libardi *et al* (1980), Kirda (1990), Jones and Wagenet (1984) and used by Baba-Kutigi, *et al.* (2006) as

$$K\left(\theta\right) = K_o \exp\left[\beta\left(\theta_o - \theta\right)\right]$$

where β is constant and K_o and θ_o are the values of K and θ at saturation, respectively. Therefore, the exponential equation describing unsaturated hydraulic conductivity is given as

$$K(\theta) = 2.64 \exp[-0.2856(84.03 - \theta)]$$

5.8.2 Result Analysis of Hydraulic Conductivity

The trend lines obtained for hydraulic conductivity with its linear regression shows soil water infiltration rate with regression r = 0.9548 and 0.912 respectively and its hydraulic conductivity was found to be in the range of 0.745 cmh^{-1} to 0.971 cmh^{-1}.

Table: 5.11. Analysis of Variance of Hydraulic conductivity

Water cont.	n	Mean	SD	SE	
Profile 10	15	59.755	3.734	0.964	
Profile 11	15	77.15	3.565	0.9205	
Profile 12	15	79.967	2.871	0.7414	
Profile 13	15	38.366	2.554	0.6594	
Profile 14	15	54.569	3.972	1.0256	
Source of variation	SS	df	MS	F	P
Within Water cont.	17567.076	4	4391.769	3845.03	<0.0001
Between Water cont.	736.76	14	52.626	46.07	<0.0001
Within cells	63.963	56	1.142		
Total	18367.799	74			

The comparative analysis as shown in Fig. 5.15 of each profile indicates that all the measurement taken is within the range. Analysis of Variance (ANOVA), standard deviation between 2.554 and 3.972, and sources of errors is between 0.6594 and 1.0256 for the five plots considered. The source of variation within volumetric water contents and between water contents has $p < 0.0001$ (see table 5.11). Soil texture for the hydraulic conductivity is either clay loam.

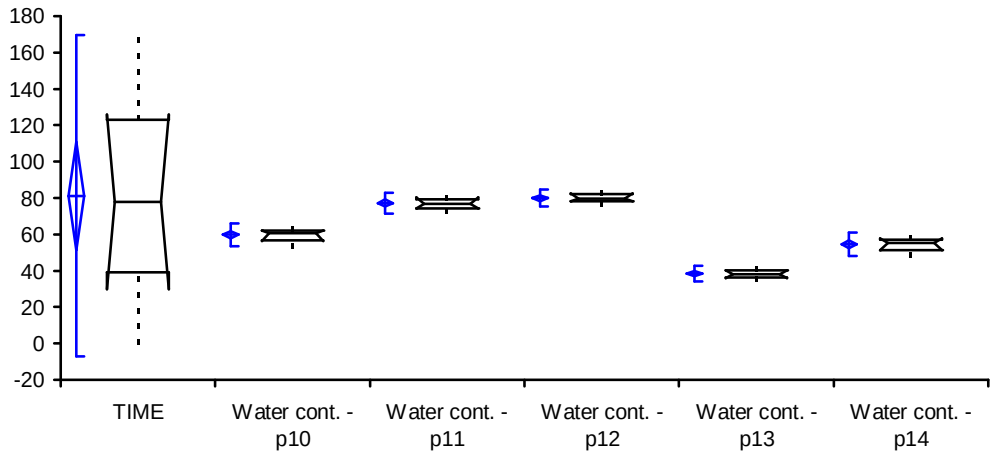

Fig. 5.15 Comparative descriptive

5.9 Grain yield

The yield can be expressed in various ways, depending on the interests of the farmers, but grain and stver is important in Northern guinea savannah, though other crop residue are equally available as animal feed. Therefore, the yield (Y) is better expressed as the above –ground dry matter and thus ignoring the root system (Kirda 1990).

Tables; 5.12, 5.13, 5.14, 5.15, and 5.16 show the grain yield in ton/hacre. Tables 5.12, 5.14 and 5.16 are the yield obtained by irrigation while Table 5.13 and 5.15 are the yield obtained on the rain fed. There are consistencies on the yield as shown on the tables.

Table 5.12 Grain yield for irrigation in t/ha for 2003 season

Treatment	Replicate				Mean ± std. dev.	Std. error
	1	2	3	4		
1	2.80	3.00	2.75	2.30	2.713 ± 0.295	0.148
2	1.80	2.00	2.10	2.00	1.975 ± 0.126	0.063
3	2.40	2.00	2.50	2.00	2.225 ± 0.263	0.132
4	2.18	2.00	1.76	1.77	1.928 ± 0.202	0.101
5	2.20	1.84	1.77	1.57	1.845 ± 0.263	0.131
6	1.66	1.68	1.68	1.60	1.655 ± 0.038	0.019

Table 5.13 Grain yield for rain season in t/ha for 2003 season

Treatment	Replicate				Mean ± std. dev.	Std. error
	1	2	3	4		
1	4.35	3.40	3.45	3.08	3.570 ± 0.545	0.273
2	3.40	4.20	3.23	3.18	3.503 ± 0.474	0.237
3	3.65	3.08	3.48	3.65	3.465 ± 0.269	0.134
4	3.43	3.30	3.33	2.80	3.215 ± 0.282	0.141
5	3.53	2.83	2.73	3.50	3.147 ± 0.427	0.213
6	3.28	3.93	3.43	3.38	3.505 ± 0.290	0.145

Table 5.14 Grain yield for irrigation in t/ha for 2004 season

Treatment	Replicate				Mean ± std. dev.	Std. error
	1	2	3	4		
1	2.4	2.5	2.5	2.0	2.350 ± 0.238	0.119
2	2.4	2.4	2.7	2.8	2.575 ± 0.206	0.103
3	2.8	2.7	2.6	2.9	2.750 ± 0.129	0.065
4	2.0	2.4	2.2	2.9	2.375 ± 0.386	0.193
5	2.6	2.6	2.2	2.2	2.400 ± 0.231	0.116
6	2.1	2.0	2.5	2.5	2.275 ± 0.263	0.132

Table 5.15 Grain yield for rain Season in t/ha for 2004

Treatment	Replicate				Mean ± std. dev.	Std. error
	1	2	3	4		
1	3.3	4.4	4.4	3.6	3.925 ± 0.562	0.281
2	4.4	4.0	3.5	3.3	3.800 ± 0.497	0.248
3	4.6	4.0	2.7	4.0	3.825 ± 0.802	0.401
4	3.4	2.4	3.5	3.6	3.225 ± 0.556	0.278
5	3.6	3.6	3.6	3.4	3.550 ± 0.100	0.05
6	3.8	2.7	4.4	3.9	3.700 ± 0.717	0.358

Table 5.16 Grain yield for irrigation in t/ha for 2005 season

Treatment	Replicate				Mean ± std. dev.	Std. error
	1	2	3	4		
1	1.8	1.6	2.9	2.2	2.125 ± 0.574	0.287
2	2.1	2.1	1.8	2.1	2.025 ± 0.150	0.075
3	2.3	2.2	2.5	1.9	2.175 ± 0.340	0.170
4	2.0	1.8	2.5	1.9	2.050 ± 0.311	0.156
5	1.9	1.5	1.6	1.3	1.575 ± 0.250	0.125
6	1.8	1.9	1.7	1.2	1.650 ± 0.311	0.156

5.9.1 Analysis of the grain yield

The yield for treatment 1 (T_1) has shown high yield and treatment 6 (T_6) has low yield in almost all replication as shown in Fig. 5.16.There is consistency on the grain yield as shown in the Fig. 5.16, 5.18 and 5.20.

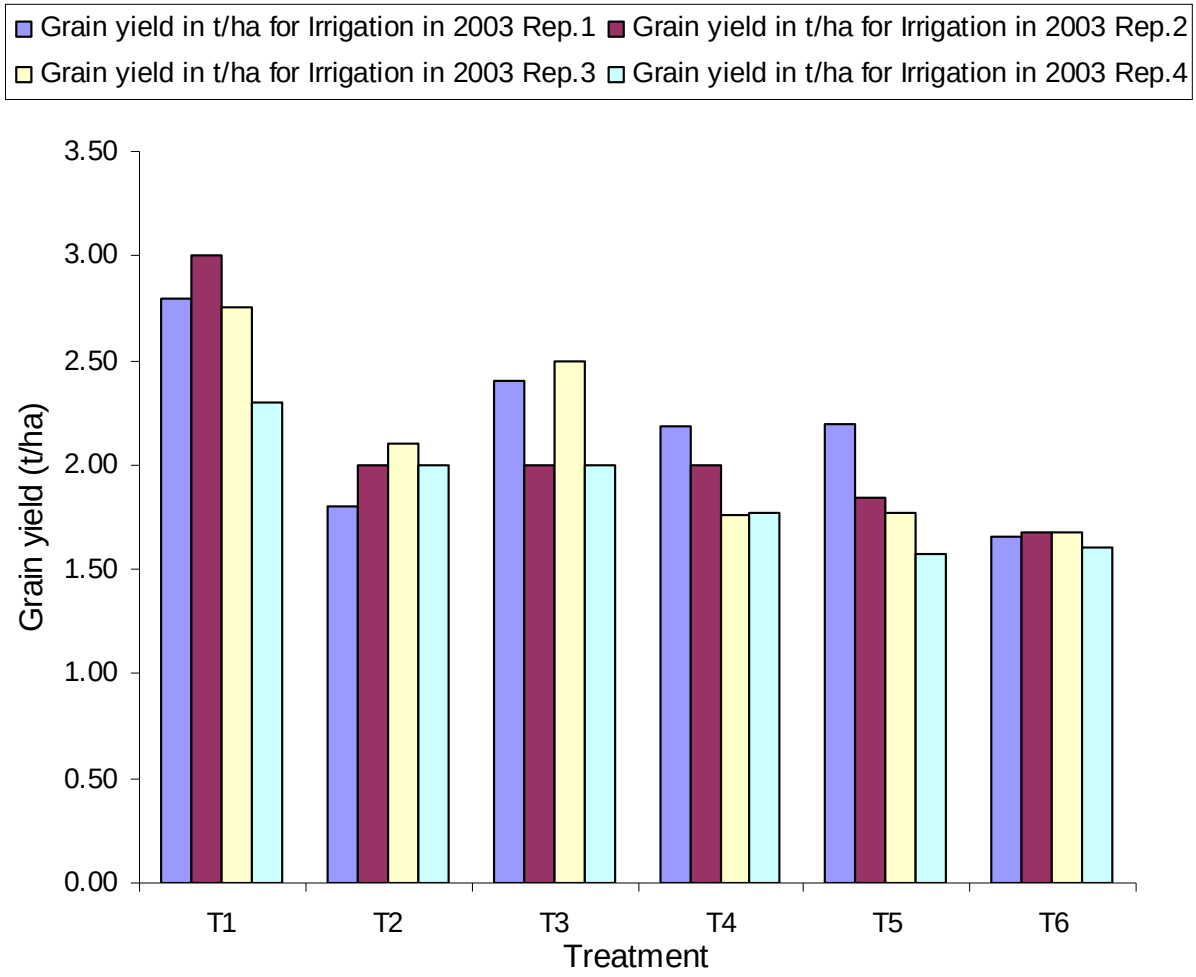

Fig. 5.16 Grain Yield in t/ha for Irrigation in 2003

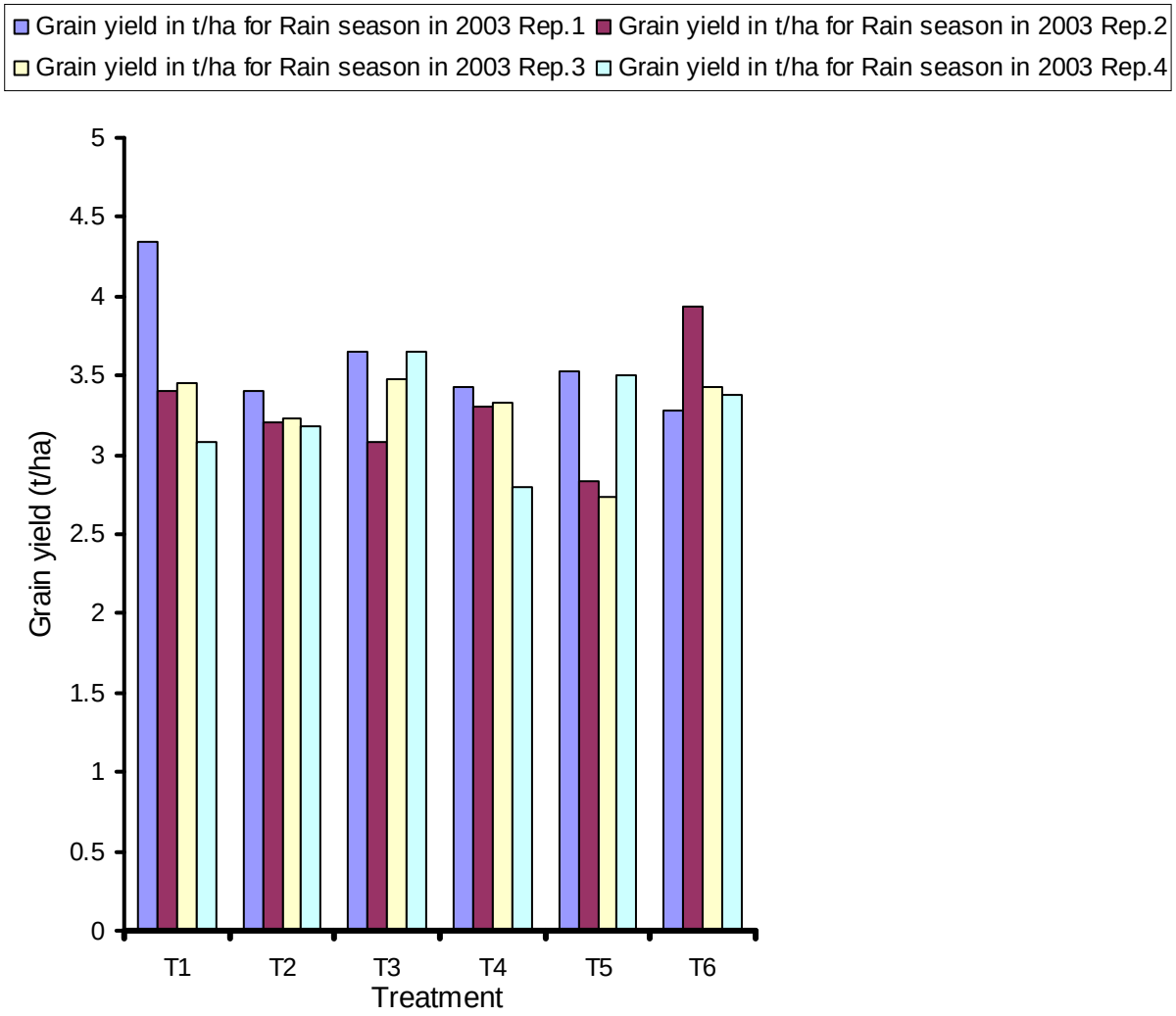

Fig. 5.17 Grain Yield (t/ha) for Rain Season in 2003

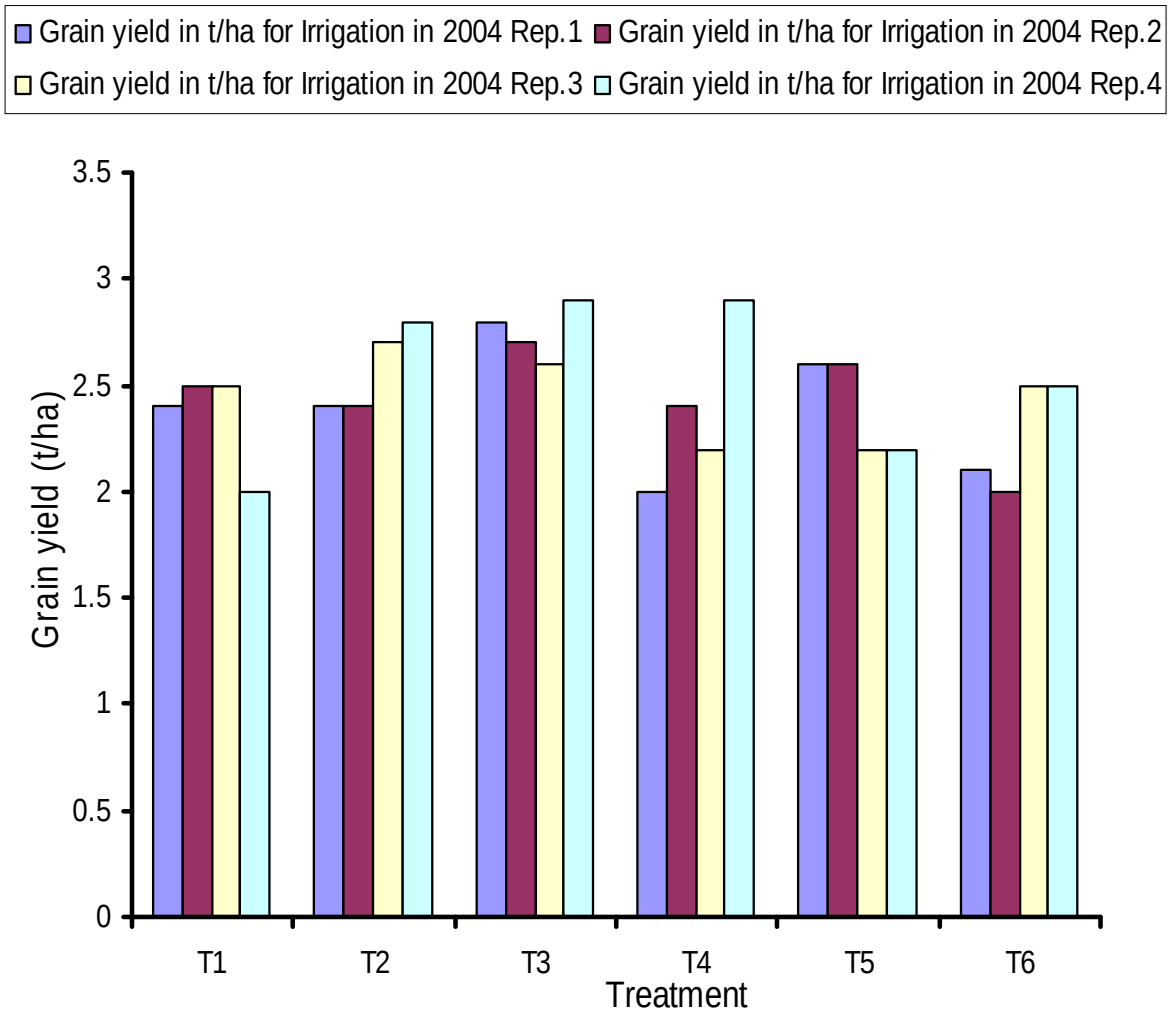

Fig.5.18 Grain Yield t/ha for Irrigation 2004

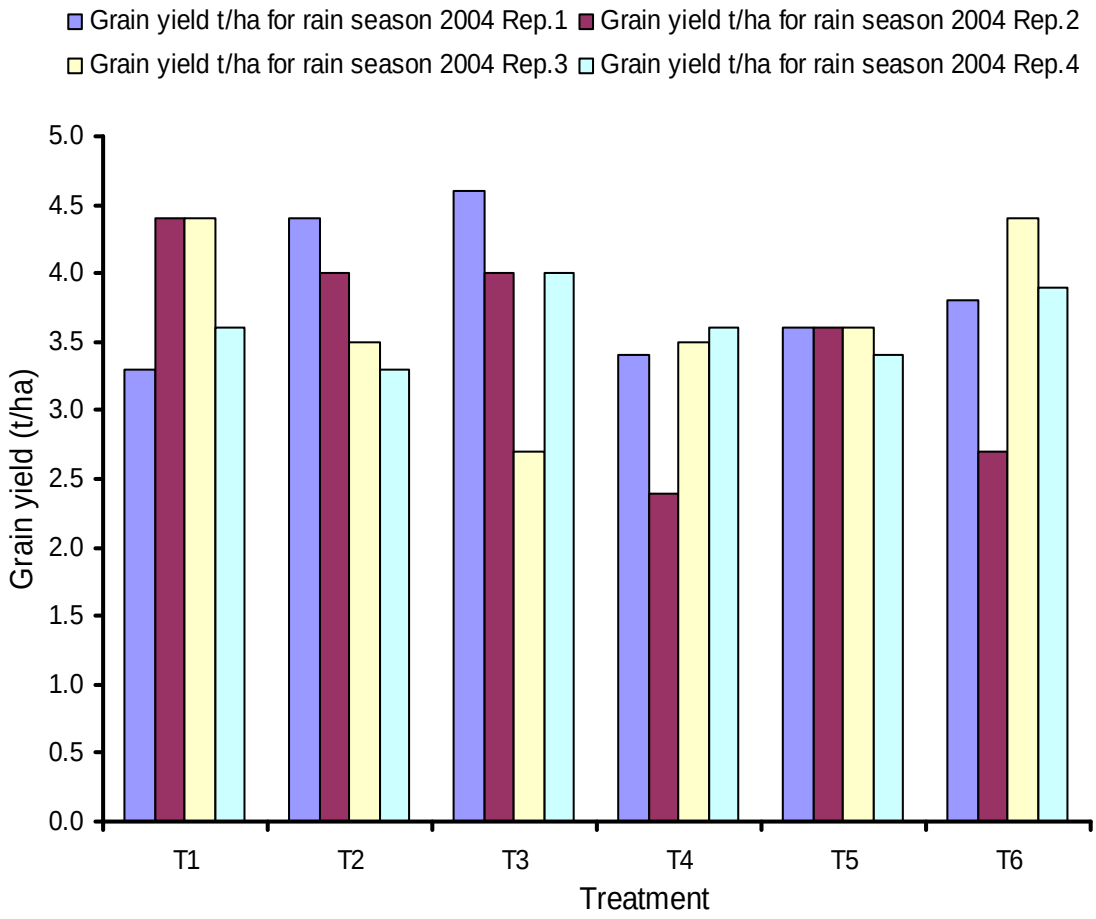

Fig. 5.19 Grain Yield t/ha for Rain Season 2004

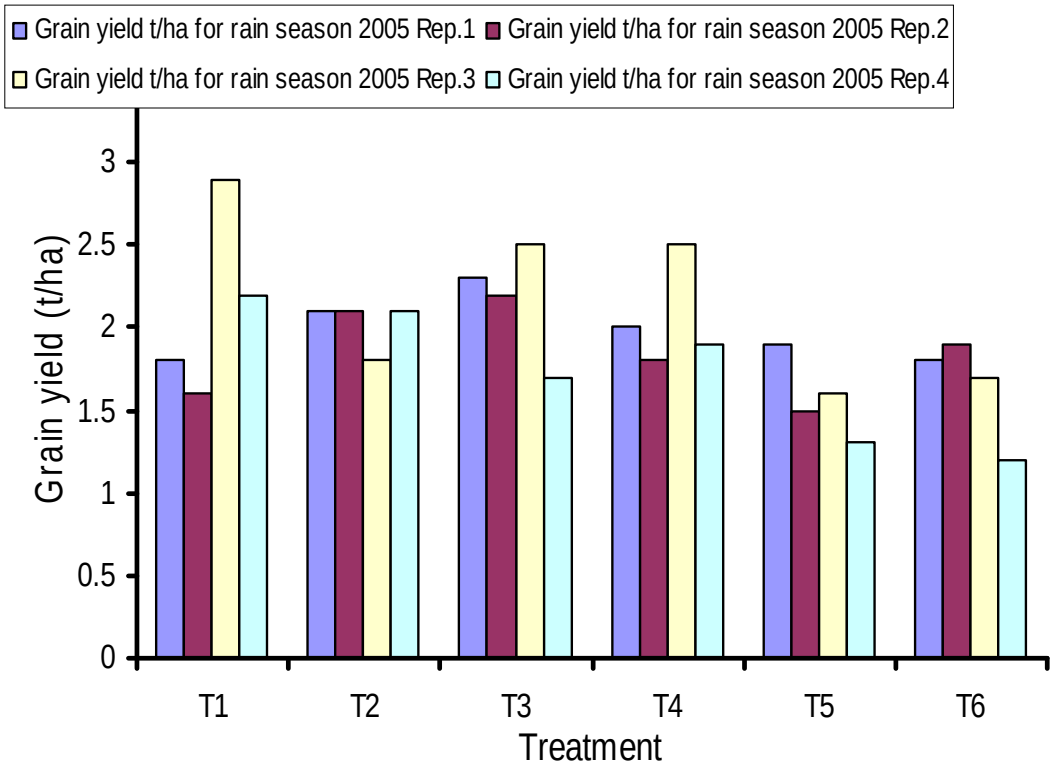

Fig. 5.20 Grain yield t/ha for irrigation 2005

5.9.1 Discussions on Grain yield

The standard error for the irrigation in 2003 ranges between 0.019 and 0.148 while that of rain season ranges 0.134 and 0.273; that for irrigation in 2004 is 0.065 and 0.193 while that of rain season 0.248 and 0.401; and that for irrigation in 2005 is 0.075 and 0.287.

The grain yield as shown on the histogram of figures 5.16 to 5.20 the consistency in the yields compared with each other in their replications and treatments.

CHAPTER 6

SUMMARY AND CONCLUSION

Soil water holding capacity is controlled primarily by the soil texture (particle size distribution of a soil) and the soil organic matter content. The small particles (clay and silt) have a much larger surface area than the larger sand particles. This large surface area allows the soil to hold a greater quantity of water. The amount of organic material in a soil also influences the water holding capacity. As the level of organic matter increases in a soil, the water holding capacity also increases, due to the affinity of organic matter for water. The upper limit (field capacity) for water content represents the maximum water contents observed in a profile for a given hydrological setting is 0.24 cm^3cm^{-3}. While the lower limit (wilting point) of the water content can be established as the measurement following a long drying period is 0.10 cm^3cm^{-3} (Greacen, 1981).

In an irrigation situation, the information's on field capacity and wilting point is necessary in determining how many cm of available water a soil profile could hold and how much water can be applied to a soil before leaching of nutrients and pesticides may occur. At vegetative (developmental) stages for the three treatments considered i.e. T_1, T_4 and T_6 the %Available water in the soil is above 50% and therefore does not matter much about the irrigation procedure employed, the plants at vegetative stages for all the treatments look greenish and of average height. However, at reproductive (establishment) stages the % Available water for the plant is below 50 %, which indicates that the plants were stressed by this treatment at this stage. During the reproductive stage, plants are generally removing nutrients from the soil at the highest rate during their life cycle, i.e. at seedling and flowering stages of maize, drought stress

set in especially with treatment T_4, T_5 and T_6 causing reduction in the yield (Kamara *et al.*, 2001).

Information on water storage in the plant root zone is widely used for decision making regarding the most suitable cropping system in a given region. Water retention capacity of soils influences water availability to plants, and can be determined with knowledge of changes in water storage in the plant root zone. A number of studies have shown that water uptake from a given volume of soil depends on the rooting density and soil water properties (Kamara *et al.*, 2001). Crop water requirements vary with stages of growth. The soil water balance equation thus helps in making estimates of parameters, which influence amount of soil water. The periods of water stress which may have adverse effect on crop performance are easily identified from soil water balance equation. This identification will help in adopting appropriate management practices to alleviate constraint and increase crop yields.

Water and contaminant migration in the unsaturated zone, have become critical to water resource development, agriculture, site restoration and waste disposal strategies. Liquid transport is much slower in an unsaturated zone. Transport through the zone is usually a limiting factor for contaminant release, nutrient loss and groundwater recharge. These necessitate the requirement for measuring unsaturated hydraulic conductivity for each geologic unit, and soil horizon to satisfy the engineering components for modeling and performance assessment needs.

Unsaturated hydraulic conductivity is an important soil property affecting water and solute transfer rate in soil. However, it is very difficult to accurately measure soil hydraulic conductivity. Therefore, indirect methods for estimating soil hydraulic properties become an important technological tool for predicting unsaturated hydraulic

conductivity from more easily measured soil properties (Wang Quajiun, 1991). The result obtain from unsaturated hydraulic conductivity determines how fast water will flow through a soil that has different initial water contents. This information is important for predicting how nutrients or pesticides may move through a soil profile.

From the result the following conclusions were reached:

1 The capacitance probe proved to be sensitive to soil moisture measurement in the soil profiles.

2 Irrigation using treatment 3 with necessary amount of water gave better yield for three seasons.

3 The rise and fall at different stages of measurement are similar for similar treatment.

4 Capacitance probe (Diviner 2000) is a practical tool to monitor changes of soil water content at least to maize root zone of about 30 cm.

5 Water stress during the tassling stages (flowering period) and water stress during yield formation has the highest adverse effect on the final yield.

6 The hydraulic conductivity in Alfisol of Northern Guinea Savannah of Nigeria was found to be in the range of 0.745 - 0.971 cmh^{-1}.

6.1 Suggestion for future work

1 There should be constant fund for further researches in the same area for at least ten years.

2 Due to acute shortage of water in this region between March and May, it is advisable to start planting in late October when rain has ceased and winter has not set in.

3 More than one probe should be provided for measurement for continuity in case of broken down equipment.

4 There should be enough water storage that could last about a week to guard against problem that may arise with tractor.

5 The project student should be funded such that he does not look other way when his attention is needed.

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APPENDIX A

Table A1: Water irrigation treatments chart for 2003

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
17/03/03	18/03/03	19/03/03	20/03/03	21/03/03	22/03/03	23/03/03
3	4	5	3,6	7	4,8	3
24/03/03	25/03/03	26/03/03	27/03/03	28/03/03	29/03/03	30/03/03
5	-	3,4,6	-	7	3,5	4,8
31/03/03	01/04/03	02/04/03	03/04/03	04/04/03	05/04/03	06/04/03
-	3,6	-	4,5	3,7	-	-
07/04/03	08/04/03	09/04/03	10/04/03	11/04/03	12/04/03	13/04/03
3,4,6&7	5	-	3	4,7	-	3,5,6
14/04/03	15/04/03	16/04/03	17/04/03	18/04/03	19/04/03	20/04/03
-	4,8	3	-	5,7	3,4,6	-
21/04/03	22/04/03	23/04/03	24/04/03	25/04/03	26/04/03	27/04/03
-	3	4,5,8	-	3,6,7	-	3
28/04/03	29/04/03	30/04/03	01/05/03	02/05/03	03/05/03	04/05/03
3,5	-	-	3,4,6,8	7	5	3
05/05/03	06/05/03	07/05/03	08/05/03	09/05/03	10/05/03	11/05/03
4	-	3,6	5	4,7,8	3	-
12/05/03	13/05/03	14/05/03	15/05/03	16/05/03	17/05/03	18/05/03
-	3,4,5,6	-	-	3,7	4,8	5
19/05/03	20/05/03	21/05/03	22/05/03	23/05/03	24/05/03	25/05/03
3,6	-	4	3	5,7	-	3,4,6,8

Table A2: Water irrigation treatments chart for 2004

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
08/03/04	09/03/04	10/03/04	11/03/04	12/03/04	13/03/04	14/04/04
-	3	4	5	3,6	7	4,8
15/03/04	16/03/04	17/03/04	18/03/04	19/03/04	20/03/04	21/03/04
3	5	-	3,4,6	-	7	3,5
22/03/04	23/03/04	24/03/04	25/03/04	26/03/04	27/03/04	28/03/04
4,8	-	3,6	-	4,5	3,7	-
29/03/04	30/03/04	31/03/04	01/04/04	02/04/04	03/04/04	04/04/04
-	3,4,5,6	5	-	3	4,7	-
05/04/04	06/04/04	07/04/04	08/04/04	09/04/04	10/04/04	11/04/04
3,5,6	-	4,8	3	-	5,7	3,4,6
12/04/04	13/04/04	14/04/04	15/04/04	16/04/04	17/04/04	18/04/04
-	-	3	4,5,8	-	3,6,7	-
19/04/04	20/04/04	21/04/04	22/04/04	23/04/04	24/04/04	25/04/04
4	3,5	-	-	3,4,6,8	7	5
26/04/04	27/04/04	28/04/04	29/04/04	30/04/04	01/05/04	02/05/04
3	4	-	3,6	5	4,7,8	3
03/05/04	04/05/04	05/05/04	06/05/04	07/05/04	08/05/04	09/05/04
-	-	3,4,5,6	-	-	3,7	4,8
17/05/04	18/05/04	19/05/04	20/05/04	21/05/04	22/05/04	23/05/04
3,4,6,8	-	-	3,5	4	7	3,6
24/05/04	25/05/04	26/0504	27/05/04	28/05/04	29/05/04	30/0504
-	5,8	3	-	-Harvest	3,4,6,8	5

Table A3: Water irrigation treatments chart for 2005

Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
14/03/05	15/03/05	16/03/05	17/03/05	18/03/05	19/03/05	20/03/05
-	-	-	planting	-	-	3
21/03/05	22/03/05	23/03/05	24/03/05	25/03/05	26/03/05	27/03/05
4	5	3,6	7	4,8	3	5
28/03/05	29/03/05	30/03/05	31/03/05	01/04/05	02/04/05	03/04/05
-	3,4,6	-	7	3,5	4,8	-
04/04/05	05/04/05	06/04/05	07/04/05	08/04/05	09/04/05	10/04/05
3,6	-	4,5	3,7	-	-	3,4,6,8
11/04/05	12/04/05	13/04/05	14/04/05	15/04/05	16/04/05	17/04/05
5	-	3	4,7	-	3,5,6	-
18/04/05	19/04/05	20/04/05	21/04/05	22/04/05	23/04/05	24/04/05
4,8	3	-	5,7	3,4,6	-	-
25/04/05	26/04/05	27/04/05	28/04/05	29/04/05	30/04/05	01/05/05
3	4,8,5	-	3,6,7	-	4	3,5
02/05/05	03/05/05	04/05/05	05/05/05	06/05/05	07/05/05	08/05/05
-	-	3,4,6,8	7	5	3	4
09/05/05	10/05/05	11/05/05	12/05/05	13/05/05	14/05/05	15/05/05
-	3,6	5	4,7,8	3	-	-
16/05/05	17/05/05	18/05/05	19/05/05	20/05/05	21/05/05	22/05/05
3,4,5,6	-	-	3,7	4,8	5	3,6
23/05/05	24/05/05	25/05/05	26/05/05	27/05/05	28/05/05	29/05/05
-	4	3	5,7	-	3,4,6,8	-
30/05/05	31/05/05	01/06/05	02/06/05	03/06/05	04/06/05	05/06/05
-	3,5	4	7	3,6	-	4,8,5

Water irrigation treatment chart for 2005 season

1. Planting : 17/03/05
2. Germination started: 20-21/03/05
3. Complete germination: 22-23/03/05
4. 1st weeding and fertilization application: 31/03/05
   Second weeding and addition of 2nd fertilizer application: 21/04/05

APPENDIX B

Table B1: Height (H) and stem (B) of the plant as at 11/04/04

H → 51.67 ± 7.533 B → 2.90 ± 0.28	H → 60.83 ± 10.426 B → 2.90 ± 0.51	H → 69.00 ± 7.384 B → 3.20 ± 0.41	H → 63.50 ± 4.765 B →3.07 ± 0.22
H →53.00 ± 5.698 B → 2.67 ± 0.23	H →52.83 ± 5.427 B → 2.60 ± 0.28	H →50.50 ± 7.187 B → 2.68 ± 0.31	H →46.67 ± 3.338 B →2.63 ± 0.35
H →54.50 ± 4.726 B →3.00 ± 0.30	H →51.50 ± 4.855 B →2.72 ± 0.39	H →49.83 ± 5.648 B →2.88 ± 0.25	H →50.33 ± 3.726 B →2.72 ± 0.25
H →41.33 ± 2.505 B →3.00 ± 0.39	H →57.68 ± 6.863 B →2.83 ± 0.14	H →57.17 ± 5.233 B →2.60 ± 0.28	H →54.33 ± 2.613 B →2.82 ± 0.25
H →42.17 ± 4.174 B →2.58 ± 0.32	H →55.17 ± 7.528 B →2.70 ± 0.52	H →54.83 ± 7.496 B →2.72 ± 0.16	H →49.33 ± 1.637 B →2.67 ± 0.25
H →48.67 ± 3.887 B →2.68 ± 0.44	H →55.00 ± 4.734 B →3.00 ± 0.35	H →51.33 ± 7.555 B →2.72 ± 0.17	H →47.50 ± 3.734 B →2.58 ± 0.30

Table B2: Height (H) and stem (B) of the plant as at 07/05/04

H →188.33 ±10.803 B →3.33 ± 0.34	H →185.11 ± 22.816 B →2.95 ± 0.33	H →197.83 ± 11.024 B →2.98 ± 0.35	H →193.5 ± 12.425 B →3.07 ± 0.22
H →164.33 ± 16.628 B →2.98 ± 0.29	H →178.83 ± 17.777 B →2.53 ± 0.27	H →189.83 ± 11.327 B →2.68 ± 0.15	H →169.67 ± 16.608 B →2.75 ± 0.39
H →187.50 ± 14.126 B →3.38 ± 0.34	H →189.33 ± 14.325 B →2.67 ± 0.15	H →159.50 ± 22.478 B →2.67 ± 0.16	H →169.00 ± 14.426 B →2.63 ± 0.37
H →178.83 ± 6.625 B →3.03 ± 0.39	H →210.83 ± 8.013 B →2.90 ± 0.09	H →220.67 ± 2.163 B →2.93 ± 0.10	H →211.83 ± 12.873 B →2.95 ± 0.14
H →183.67 ± 8.454 B →2.87 ± 0.23	H →170.33 ± 15.538 B →2.73 ± 0.39	H →181.33 ± 10.56 B →2.63 ± 0.18	H →179.33 ± 9.547 B →2.57 ± 0.21
H →162.83 ± 9.587 B →2.48 ± 0.19	H →194.67 ± 11.414 B →2.85 ± 0.27	H →199.67 ± 14.375 B →2.78 ± 0.25	H →187.17 ± 15.384 B →2.77 ± 0.21

APPENDIX C: Conversion Factors

Length

	cm	m	km	in	ft	mi
1 cm	1	10^{-2}	10^{-5}	0.3937	3.281×10^{-2}	6.214×10^{-6}
1 m	100	1	10^{-3}	39.37	3.281	6.214×10^{-4}
1 km	10^{5}	1000	1	3.937×10^{4}	3281	0.6214
1 in	2.54	2.54×10^{-2}	2.54×10^{-5}	1	8.333×10^{-2}	1.578×10^{-5}
1 ft	30.48	0.3048	3.048×10^{-4}	12	1	1.894×10^{-4}
1 mi	1.609×10^{5}	1609	1.609	6.636×10^{4}	5280	1

1 angstrom = 10^{-10} m 1 fermi = 10^{-12} m
1 yard = 3 ft 1 mile = 1852 m
1 mile = 10^{-2} in 1 Bohr radius = 5.292×10^{-11}

Area

	m^2	cm^2	ft^2	$in.^2$
1 Sq.m	1	10^{4}	10.76	1550
1 Sq.cm	10^{-4}	1	1.076×10^{-3}	0.1550
1 Sq.ft	9.290×10^{-2}	929.0	1	144
1 Sq.in	6.452×10^{-4}	6.452	6.944×10^{-3}	1

1 Square mile = 2.788×10^{6} ft^2 = 640 acres
1 acre = 43,600ft^2

Volume

	m^3	cm^3	li	ft^3	$in.^3$
1 cubic meter	1	10^{6}	1000	35.31	6.102×10^{4}
1 cubic cm.	10^{-6}	1	1.0×10^{-3}	3.531×10^{-5}	6.102×10^{-2}
1 liter	1.0×10^{-3}	1000	1	3.531×10^{-2}	61.02
1 cubic foot	2.832×10^{-6}	2.832×10^{4}	28.32	1	1728
1 cubic inch	1.639×10^{-5}	16.39	1.639×10^{-2}	5.787×10^{-4}	1

1 liter = 10^{-3} m^3

APPENDIX D

Table D1: Hydraulic conductivity

TEXTURE	STRUCTURE	INDICATIVE HYDRAULIC CONDUCTIVITY, *K*	
		(cm/h)	(m/day)
Coarse sand, gravel	Single grain	>= 50	>= 12
Medium sand	Single grain	25 – 50	6 – 12
Loamy sand, fine sand	Medium crumb, single grain	12 – 25	3 – 6
Fine sand loam, sandy loam	Coarse, sub angular blocky & granular, fine crumb	6 – 12	1.5 – 3
Light clay loam, silt, silt loam, very fine sand loam, loam	Medium prismatic & sub angular blocky	2 – 6	0.5 – 1.5
Clay, silt clay, sandy clay, silt clay loam, silt loam, silt, sandy clay loam	Fine medium & prismatic, angular blocky, platy	0.5 – 2	0.1 – 0.5
Clay, clay loam, silt clay, sandy clay loam	Very fine or fine prismatic, angular blocky, platy	0.25 – 0.5	0.05 – 0.1
Clay, heavy clay	Massive, very fine or fine columnar	< 0.25	< 0.05

Source: - Adapted from FAO (1979a, p177)

Table D2: Hydraulic Conductivity (*K*)

Hydraulic Conductivity (*K*)		Conductivity class
(m/day)	(cm/h)	
< 0.2	< 0.8	Very slow
0.2 – 0.5	0.8 –2.0	Slow
0.5 – 1.4	2.0 – 6.0	Moderate
1.4 – 1.9	6.0 – 8.0	Moderately rapid
1.9 – 3.0	8.0 – 12.5	Rapid
> 3.0	> 12.5	Very rapid

Source: - adapted FAO (1963)

APPENDIX E1: STASTISTICAL SUMMARY OUTPUT OF WUE FOR 2003

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.898607902
R Square	0.807496162
Adjusted R Square	0.798745987
Standard Error	2.225528236
Observations	24

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	457.0776345	457.0776	92.28344	2.49366E-09
Residual	22	108.9654704	4.952976		
Total	23	566.0431049			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	2.745034734	0.679484689	4.039877	0.000547	1.335868225	4.154201	1.3358682	4.15420124
NUE	0.012648506	0.001316671	9.606427	2.49E-09	0.009917894	0.015379	0.0099179	0.01537912

APPENDIX E2: STASTISTICAL SUMMARY OUTPUT OF WUE FOR 2004

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.956866831
R Square	0.915594132
Adjusted R Square	0.910904918
Standard Error	4.632856153
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	4190.834397	4190.834	195.2553	4.19562E-11
Residual	18	386.3404104	21.46336		
Total	19	4577.174808			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	38.78314223	2.535544649	15.29578	9.29E-12	33.45615647	44.110128	33.45615647	44.110128
WUE	6.149676935	0.440099492	13.97338	4.2E-11	5.225061497	7.0742924	5.225061497	7.07429237

APPENDIX E3: STASTISTICAL SUMMARY OUTPUT OF WUE FOR 2005

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.94678141
R Square	0.896395038
Adjusted R Square	0.891461468
Standard Error	2.925654465
Observations	23

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1555.192834	1555.193	181.6929941	8.29374E-12
Residual	21	179.748535	8.559454		
Total	22	1734.941369			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	24.8041922	2.066549332	12.00271	7.25137E-11	20.50656685	29.10182	20.50656685	29.1018175
WUE	7.576571898	0.562087151	13.47935	8.29374E-12	6.407647473	8.745496	6.407647473	8.74549632