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AHMADU BELLO UNIVERSITY, ZARIA

EVALUATION OF SELECTED CROP YIELD WATER USE MODELS FOR A WHEAT CROP.

BY

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Being a thesis submitted to the Post Graduate School, Ahmadu Bello University, Zaria, in partial fulfillment of the requirement for the award of Master of Science degree in Agricultural Engineering.

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DECLARATION

I hereby declare that this thesis has been written by my self and that it is a record of my research work. It has not been submitted or accepted in any previous application for a Higher Degree. All sources of information have been specifically acknowledged by means of reference.



22-12-97

HENRY E. IGBADUN DATE

CERTIFICATION

This thesis, entitled "EVALUATION OF SELECTED CROP YIELD-WATER USE MODELS FOR A WHEAT CROP" by H.E.Igbadun, meets the regulations governing the award of the Degree of Master of Science (Agric. Engineering) of Ahmadu Bello University, Zaria, and is approved for its contibution to Scientific/Technical knowledge and literary presentation.

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DEDICATION

To

the Lord Jesus Christ, the author and finisher of our faith (Heb. 12:2), and to my late friend and brother, Bro. Emmanuel Idowu Isehunwa who died on 17th November, 1996. Bro, you were a friend indeed to this work. This is a worthy dedication. We shall meet again on the resurrection morning, at the feet of our Master, Lord and Saviour Jesus Christ. See you then.

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ABSTRACT

Relationships between crop yields (dry matter and grain yields) and seasonal evapotranspiration for wheat in Samaru- Zaria, Nigeria, under conditions of moisture stress caused by evapotranspiration deficits at four growth stages of the wheat crop are presented. Wheat, (Triticum aestivum L.CV. sete ceros) was planted in the Institute for Agricultural Research (I..R.) farm during the 1995/96 cool harmattan season, under irrigation. Evapotranspiration deficits were created by withholding irrigation for some days in excess of the regular 7 day irrigation interval at each of the four growth stages considered. The resultant moisture stress affected grain and dry matter yields. Crop water use was monitored throughout the season for each treatment and grain and dry matter yields were recorded at harvest.

Two multiplicative crop yield models: Jensen(1968) and Minnas et al (1974); and two additive models: Stewart et al (1977) and Bras and Cordova (1981) were evaluated using the experimental data, and their stress sensitivity factors estimated for the four growth stages considered. Their accuracy and predictability of crop yields were also tested. The results indicated that strong linear relationships exist between grain and dry matter yields and seasonal evapotranspiration within the limits tested. An evapotranspiration (ET) threshold of 69.3mm is required for dry matter yield initiation, while an ET threshold of 145mm is required for grain yield. Thereafter, an increment of 10.2 kg/ha in grain yield and 22.5kg/ha in dry matter yield is expected for every mm of crop

water use. The four models, using the estimated stress sensitivity factors, were found to adequately predict crop yield. However, the Jensen (1968) and Bras and Cordova(198l) models predicted closer results than the others.

The grain yield losses due to the moisture stress caused by the evapotranspiration deficits were relatively equal to the dry matter yield losses at booting to heading stage, and at soft dough to hard dough development, while moisture stress at flowering to milkdough development had greater yield reduction effect on the grain yield than dry matter yield.

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INTRODUCTION

The first step in energy and water conservation in irrigation is the elimination of needles wastes. A sound management of irrigation entails an irrigation schedule which requires giving the right quantity of water to the crops at the right time such that crop yield is not affected as a result of moisture stress or waterlogging. Moisture stress herein is as defined by Craft (1968) as the state a plant enters when the water potential is sufficiently low to inhibit normal plant physiological processes. Generally, when full crop water requirement is not met, water deficit in the plant can develop to a point where crop growth and yields are adversely affected. The manner in which deficit affects crop growth and yield varies with the crop species, the crop growth stage and the degree of the deficit (Doorenbos and Kassam, 1979). Thus, water supply is adequate only if irrigation is scheduled such that the soil water content in the crop root zone, throughout the crop growing season, can be at levels which do not limit crop growth and yield.

The ultimate objective of an irrigator is to schedule his irrigation in order to maximize his profit from the irrigated crop production. In order to do this, he requires knowledge both of the cost of applying each increment of water and the additional benefit arising from the increase in yield associated with each increment of water applied. He needs a quantitative information concerning crop response to water deficit due to both magnitude and time of occurrence. Although, the upper limit of crop yield is set by the climatic conditions and the genetic potential of the crop, the extent to which this limit can be reached will

always depend on how finely the engineering aspect of water supply are in tune with the biological needs for water in crop production. Therefore, efficient use of water in crop production can only be attained when the planning, design and operation of the water supply and distribution systems are geared towards meeting in quantity and time the crop water needs required for optimum growth and high yield.

According to Singh (1981), water management which uses potential evapotranspiration (ETP) as a guide to irrigation for high yields is applicable when land is limited and water supply is unlimited. In arid regions where water must be carefully managed, an optimization approach applicable to the of a limited water supply is suggested. The approach is to increase water use efficiency by raising the crop yield and simultaneously applying water in amounts less than the actual seasonal evapotranspiration (SET) requirement. Such management of a limited water supply results in an inevitable introduction of some evapotranspiration deficits (ETd) during the cropping period. Thus, the optimal timing or sequencing of the desired ETd which results in definable minimum reduction in yield below the maximum (Ym) becomes important. This requires the quantitative knowledge of the critical growth stages for the crop and the order of their relative sensitivity to water deficit. Thus, the relationship between water use and crop yield are of great importance.

According to Minhas et al (1974), in studying the question of economic optimal use of water, we need to know the exact shape of the crop response

function to different quantities of water use by the crop throughout the growth stages. It is a well known fact that certain growth stages of crop are more sensitive to water deficits than others. Thus, a knowledge of the marginal productivity of water allocated to each crop at different stages of its growth is required to arrive at an optimal set of decisions. Minhas et al (1974) and Stewart et al (1973) stated that this knowledge is also required in determining the command area of an irrigation system , and concluded that a production function for each crop in which yield is related to water inputs will provide such knowledge. These functions they further stated can offer extremely powerful tool for a rational design and effective production and mangement of irrigation systems. Crop-water production functions derived from experiments are usually valid only near the location where they are provided (Taskiris, 1982). This is because the absolute quantity of water to produce a given yield differs greatly between locations. Moreso, since no crop-water production function (also referred to as crop-yield model) is presently universally applicable to all crops, growing seasons and climates (Rhenals and Bras, 1981), it becomes necessary to formulate, validate or evaluate crop yield models for different locations and crops.

Research studies on the effects of moisture stress on yield and yield components of wheat crop have been carried out at the Institute for Agricultural Research (I.A.R.) Samaru by some investigators (Datiri, 1982, Chari, 1980; and Falaki, 1994). Apart from the fact that some of these works were carried out at

Kadawa Irrigation Research Project in Kano state where there is the problem of high water table, no attempt was made in any of these work to relate the crop yield to evapotranspiration, a term considered as a better predicator of crop yield (Rhenals and Bras, 1981). Thus, an area of research study in wheat production yet unexplored in this area is the aspect of crop yield-water use relationships by which crop yields and yield decreases due to plant water deficits can be quantified. Jensen(1975) stated that the reason why irrigation farm managers/operators are not greatly receptive to any particular irrigation scheduling, despite their availability, is that yield reduction caused by delayed irrigation, improper fertilization and excessive irrigation are not easily recognised or quantified by them. Such recognition and quantification are made possible and practicable by using crop water production functions. The results of suchs study therefore, will go a long way to assist in the planning and design of irrigation systems and scheduling strategies under limited water supply or where maximizing yield per unit of water use is a desired objective. Extension workers can also use the results of this study to assist farmers to easily recognise and forecast yield expected from an irrigation scheduling method under limited water supply.

1.1 Objectives:

The general objective of the study reported herein is to study and establish relationships between crop yield (both total dry matter and economic grain yields) and crop water use for wheat crop in Samaru under moisture stress conditions caused by evapotranspiration deficits at four growth stages.

The specific objectives are:

1. To establish a relationship between crop yield (grain and dry matter yield) and seasonal evapotranspiration of the wheat crop.
2. To evaluate some crop yield-water use models by studying their parameters and test their applicability and accuracy for four selected growth stages of the wheat crop
3. To study the effects of the evapotranspiration deficits on grain yield, dry matter yield, and water use efficiency (WUE) of the wheat crop.

2. REVIEW OF LITERATURE

2.1 Introduction:

Water performs a vital role as a solvent of mineral nutrient being translocated in solution throughout the plant body. It is essential for the plant to support the continuous metabolic activities inside the tissues such as regulation of body temperature and maintenance of the thermal balance of the plant at levels suitable for sustaining life and growth (Slatyer, 1967). Water is thus an important elements that determines the level of crop yield. According to Doorenbos and Kassam(1979), when climatic and agronomic conditions are adequate, crop yield becomes completely dependent on the amount of water available for use by the crops. When economic conditions do not restrict crop production and in a constraint - free condition, crop yield is at the maximum when full water requirement are met. When full water requirement are not met, water deficit in the plant can develop to a point where crop growth and yield are adversely affected.

The relationship between water and crop yield is not a simple one. In addition to soil moisture, several variables which includes: climatic factors such are temperature, solar radiation, wind velocity, relative humidity; genetic and physiological factors; diseases and pests; and hydrometeorological hazards, also affects crop production. Some of these variables are even difficult or impossible to control. Despite the influence of these variables, a great deal have been published on the aspects of water relations in crop growth, and attempts to

understand crop response to water through crop growth modelling have been successful (Doorenbos and Kassam, 1979).

According to Vaux Jr. and Pruitt (1983), Scientific research on the relationship between crop yield and water use have been motivated by the desire to determine the quantity of water that a plant requires if water is not to limit growth or productivity. They classified scientific literature on crop-water production functions into three : early related studies which physically tried to related crop yield to water use with the objective of determining the minimum soil water content or soil water potentials at which the maximum yield could be achieved; the physiological approach methods; and, the semi empirical approaches which are those characterised by efforts to relate crop yield to either soil moisture content, or soil moisture tensions; transpiration or evapotranspiration; or applied irrigation water. Presently, most of the semi-empirical models found in literature are those that relate crop yield to transpiration or evapotranspiration (Vaux and Pruitt, 1983). This study is directed towards studying some of these semi-empirical models in which crop yields are directly related to evapotranspiration or evapotranspiration deficits.

2.2. Moisture Stress and Development in Plants.

Moisture stress refers to the physiological condition of water in plants which are not favourable for optimal plant growth. It is a state when moisture supply is inadequate or a state a plant attains when the water potential is

sufficiently low to inhibit normal plant processes (Craft, 1968). This condition, according to Taylor (1968) is not the same for all plant species and varieties, and may even be different within the same plant at different times or growth stages. Moisture stress is influenced directly by plant water status and indirectly by soil water status. (Datiri, 1982) Moisture stress occurs as a result of the development of plant water deficit and not necessarily soil water deficit since with adequate soil moisture supply, plant water deficit can still occur as a result of high evaporative demand of the atmosphere. Thus, at any given soil water condition the plant may show no symptom of stress if either the atmospheric desiccating conditions are low, that is, high humidity, moderate to low temperature and no wind; or if the internal solute concentration of the tissues is high (Taylor, 1968). However, stress due to high solute concentration of the plant tissue, that is, high salt concentration or high sugar content of the cells and tissues, causes the plant to develop thick and heavy cell walls and exhibit no visible symptom. Stress due to water deficit or high evaporative demand may induce moderate to severe wilting symptoms in the plant.

Water deficit development in plant is said to be as a result of an inevitable consequence of water flow along a pathway (root tissues,stem and leaf) in which frictional resistances and gravitational potentials have to be overcome (Javis, 1975). As water evaporates from the mesophyll cells of the leaves, the water potential of the cell wall matrix adjacent to the liquid-air interface falls, and water moves towards the interface from sources of higher water potentials distributed

both throughout the plant and in the soil. Consequently, a progressive reduction in the soil water content and soil water potential results (Begg and Turner, 1976). Since there must be a potential gradient through the pathway, from the soil to the atmosphere to provide a driving force for water to flow, it follows that there is usually a concomitant water potential decline as evapotranspiration progresses which results in the development of an internal water deficit in the leaf, stem and root tissues (Slatyer, 1967). Slatyer (1967) further emphasised that the degree to which an internal water deficit develops in the leaves of a plant depends on the evaporative demand, the soil water potential at the root surface and the gradient of water potential within the plant.

2.3. Effects of Moisture Stress at Various Growth Stages on Yield Wheat.

Moisture stress in wheat generally reduces yield. The degree of yield reduction depends on the environmental condition, soil, crop variety and the growth stage at which the stress occurred (Lehane and Staple, 1962). According to Stegman et al (1980a) growth limiting stress causes reduced leaf area and plant size if it occurs in the early vegetative period. This is because water stress at this stage effects the morphological processes by suppressing cells division and elongation, suppressing tillering and increasing tiller senescence especially the ones that emerged just before the stress was imposed. Water stress in wheat imposed before heading also reduces plant height considerably (Datiri, 1982), causing marked reduction in dry matter yield.

At the jointing stages moisture stress reduces crop yield due to reduction in plant size, the number of effective tiller, and the number of spikelet per head (Days and Intalap, 1970). Falaki et al (1979) found that moisture stress at flowering influences the number of effective heads and the number of seeds per head. Hutcheon and Rennie (1960) as reported by Campbell (1968) found that a single stress at any stage of growth of wheat significantly decreased grain yield, especially if the stress was applied at the doughing stage. Bunting and Drenmand (1966) also found that moisture stress at grain filling stage including both milk and hard dough stages, reduced yield due to reduction in grain size. Robins and Domingo (1962) reported a yield reduction of 19 to 35 % in irrigated wheat resulting from severe stress imposed during and after florescence emergence.

El- Nadi (1969) reported that yield was not reduced during the vegetative period if the crop received favourable water regime thereafter; and Hsaio (1973) supported this in his report that growth limiting stress in the early vegetative period causing reduced leaf area and plant size will often minimally affect yield of a reproductive organ because reduced leaf area can allow greater canopy light penetration to maintain assimilative capacity. This is consistent with the findings of Lehane and Staple (1962) that moisture stress at an early stage of growth does not appreciable affect grain yield.

2.3.1. Critical Growth Stages of Wheat

Singh (1981) defined the critical growth stage of a crop as that stage of growth in the plant when it is most sensitive to moisture stress, causing severe

reduction in yield. Days and Intalap (1970) reported that the jointing stage of growth is the most sensitive (critical) in wheat since moisture stress at this stage reduces crop yield due to reduction in plant size, photosynthetic area and seed per spike. However, Salter and Goode (1967) in their extensive review of literature on yield response to water deficit, concluded that for wheat, the stem elongation and heading stages of growth are particularly sensitive to water stress, since the size and length of spike and the number of spikelets per spike are initiated and formed at these stages. Also, Misra et al (1969) suggested that the vegetative and soft dough period are most sensitive. Wardlaw (1971) reported that evapotranspiration deficit for even a short period after heading significantly reduces the grain weight per head. In Nigeria, Falaki et al. (1979), Chari (1980) and Datiri (1982) reported that the critical growth stage of wheat is the flowering stage, but Surma et al., (1980) reported that the jointing stage is the most sensitive to water stress.

The different conclusion reached in the subject of critical growth stage can be mainly attributed to different definitions of the length of the growth stages and the degree of stress imposed. Other factors such as root development and water use efficiency can also be significant.

2.3.2. Crop Harvest Index (HI)

Generally, for any crop only a part of the total dry matter is harvested. When wheat is grown for grain, only a fraction of the total dry matter, that is, economic grain yield is harvested. The ratio of the net harvested yield (the grains

only) and the net total above ground dry matter is known as the Harvest Index (HI), that is,

$$HI = \frac{Economic\ grain\ yield}{Total\ dry\ matter} \qquad \ldots\ldots\ldots (2.1)$$

The Harvest Index is the fraction of the total plant assimilate that was converted to grain during the growing season. For high yielding variety of wheat under irrigation, the Harvest Index ranges from 0.3 to 0.4 (Doorenbos and Kassan, 1979).

2.4. Evapotranspiration

Evapotranspiration (ET) is the sum total of water lost by transpiration from the crop and evaporation from the soil or exterior portion of the plant where water may have accumulated from rainfall, dew or exudation from the interior of the plant. The word consumptive use (or water use) for all practical purposes is identical with evapotranspiration. It may differ by the inclusion of water retained in the plant tissues, which is always insignificant when compared with evapotranspiration (Jensen, 1968).

Potential evapotranspiration (ETp) is defined by Burman et al (1983) as the maximum rate at which water, if fully available would be removed from the earth's surface and transpired by the plant, expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area. Thus, it is the evapotranspiration that occurs when the vapour pressure at the evaporating surface is at the saturation point.

Maximum evapotranspiration (ETm), as defined by Doorenbos and

Kassam (1979) is the crop water requirement needed for unrestricted optimum growth and yield of crop. It represents the rate of evapotranspiration of a healthy crop, growing in a large field under optimum agronomic and irrigation management. This level of evapotranspiration has been shown to be related to the evaporative demand of the atmosphere which is the potential evapotranspiration (ETp). For a given climate, crop and crop growth stage, the maximum evapotranspiration (ETm) in mm/day of the period considered is, (Doorenbos and Kassam; 1979).

$$ETm = Kc \times ETp \qquad \ldots\ldots\ldots\ldots 2.2$$

in which Kc is an empirically determined crop coefficient.

Actual evapotranspiration (ETa) refers to the actual crop water use at a given time. The demand for water by the crop must be met by the soil water via the plant-root system. The actual rate of water uptake by the crop from the soil at a given time in relation to its maximum evapotranspiration is determined by the amount of water in the soil (Doorenbos and Kassam, 1979). Therefore in order to determine actual evapotranspiration, the level of the available soil water must be considered. Actual evapotranspiration(ETa) will be equal to maximum evapotranspiration (ETa = ETm) when the available soil water is unlimited. Maximum evapotranspiration will be maintained when a field is irrigated until a fraction of the available water is depleted, after which actual evapotranspiration becomes increasingly smaller than the maximum until the next irrigation or heavy rain. The magnitude of ETa will now depend on the remaining available water

in the soil and the evaporative demand of the atmosphere.

2.4.1. Relative Evapotranspiration Deficit.

Doorenbos and Kassam (1979) expressed the relative evapotranspiration deficit (ETd_r) as

$$ETd_r = \left(1 - \frac{ETa}{ETm}\right) \qquad \ldots\ldots 2.3$$

in which ETa and ETm are as defined previously.

As the soil water content decreases due to evapotranspiration, and is not replenished by rainfall or irrigation, the effective hydraulic resistance increases greatly. Thus, evapotranspiration begins to fall below the actual demand or requirement of the crop. This deficit results in various degrees of plant water stress depending on the evaporative demand and plant characteristics and growth stage (Jensen, 1968), and consequently causes reduction in crop yield below the maximum or level attainable when such deficit does not occur.

2.4.2. Evapotranspiration Measurement

The basic principles and methodology of evapotranspiration measurements are broadly classified as actual evapotranspiration methods and potential evapotranspiration methods (Bungwon 1993).These principles and methodology not reviewed in this work as more detailed discussions are readily available in the literature (Tanner 1968 and Jensen 1968). Only the soil water budget approach used in this study is reviewed.The water budget method is a direct method of measuring evapotranspiration which is suitable for areas where soil is fairly

uniform and the depth of ground water is such that it will not influence the changes in soil moisture fluctuation within the root zone (Michael, 1978). It involves monitoring the changes in soil moisture content between irrigations in the major root zone depth. Evapotranspiration is regarded as the change in moisture depth between successive measurement dates of soil moisture content. The expression is given by (Michael, 1978):

$$ET = \sum_{i=1}^{n} \frac{MC_{i-1} - MC_i}{100} \cdot Asj \cdot Dj \qquad \ldots\ldots 2.4$$

Where : ET = evapotranspiration in the entire root zone depth

M_i = Gravimetric soil moisture content on day i

MC_{i-1} = gravimetric moisture content on day i-1

As_j = Specific gravity of soil layer j

D_j = Depth of layer j

n = number of depths within the profile under consideration

The soil water budget method of estimating evapotranspiration as expressed in Eq 2.4 assumes that drainage losses are negligible so that evapotranspiration is the only depletion mechanism of the soil moisture content of the soil profile. Soil moisture content determination is therefore advised to be taken some two or three days after each heavy irrigation so as to give enough time for free drainage within the crop root zone. This method of measuring evapotranspiration is cheap and easy but changes in moisture content within the soil profile depth is greatly influenced by movement of water within the profile.

2.5. Crop Yield as a function of Water use.

Attempts to develop production functions for irrigated crops are numerous. As reported by Barrett and Skogerber (1980), one of the most comprehensive studies of the dry matter yield and transpiration relationship was that of Dewit (1958) who studied a wide range of data collected for common field crops grown in containers. In the few cases where the relationship deviated from linearity, Dewit (1958) attributed such to poor aeration of the root system.. Arkley (1963) plotted dry matter yield versus transpiration corrected for mean relative atmospheric humidity during the period of the most active growth. All the graphs plotted from sites around the world and for a wide range of crops including wheat, oats, maize, millets, alfalfa and carrots showed linear relationships with very high correlation coefficients. In most cases, the line of best fit passed through the origin showing that dry matter yield was directly proportional to the transpiration(Barrett and Skogerber, 1980). Similar relationships between dry matter yield and transpiration were obtained by Hanks et. al (1969) for sorghum, wheat, oats and millet at Akron, Colorado. However when the dry matter yield was plotted against evapotranspiration, the relationship, though linear, did not pass through the origin; but to the right. Hillel and Guron's (1973) experimental results showed that there appears to be a distinct intercept or threshold value of evapotranspiration below which crop yield is negligible. They concluded that crop yield is not proportional to evapotranspiration as it is often assumed, and that even if crop yield appears to be linear with evapotranspiration, the function does

not pass through the origin. The threshold evapotranspiration value may be due largely to the water loss caused by direct evaporation from the soil surface before the plant cover begins to accumulate measurable dry matter or grain yield, and perhaps, from senescing plant after the cessation of growth.

According to Stegman et al (1980a), plotting the ratio of actual yield to maximum yield (Ya/Ym) versus actual evapotranspiration to maximum evapotranspiration (ETa/ETm) is a better way of generalising yield function since site - specific variable such as climate may produce different absolute evapotranspiration values for the same amount of growth. Thus, the use of relative evapotranspiration should permit some degree of site transferability for the production function. The fitted curve of the relative relationship also does not pass through the origin but intersects the ETa/ETm axis at a value of the order of 0.05 - 0.10 (Hanks et al, 1969), and may be as high as 0.25 - 0.50 (Stegman et al, 1980b). The intercept tends to occur at the lower end of this range when the crops are stress tolerant or when stresses are ideally distributed between the vegetative, reproductive and grain filling stages, and at the higher end of the range when stresses are extreme and or occurred at the most sensitive growth stages of the sensitive crops (Stegman et al, 1980).

2.6. Crop Yield - Water Use Models.

Numerous expressions have been suggested in an attempt to relate crop yield to water use. Some investigators related yield to transpiration or evapotranspiration; others to water applied, and some still, to some factors such

as soil moisture depletion, climatic and cultural factors. Vaux Jr. and Pruitt (1983) broadly classified these functions into what they called "agronomic formulations" and "economic formulations". The economic formulated models are based on the premise of conventional economic theories which provide an adequate frame work for analysing crop-water production relation. The agronomic formulated ones are those derived empirically from irrigation experiments designed to determine crop sensitivity factors to water deficits at specified periods of growth which usually coincide with the phenological stages of the crop. Only the agronomic formulated models are considered in this study. The four growth stages considered were: stem elongation to booting initiation; Booting to full heading; flowering to milk-dough development; and soft dough to hard dough development. These growth stages were selected because, according to Singh (1981), in planning strategies for efficient use of limited water supplies, the crop response to an evapotranspiration deficit at jointing (stem elongation), heading, flowering and early grain development stages of a crop are important since moisture stress at these stages causes significant reduction of the crop yields.The crop water production functions are formulated by postulating that water deficits in each period (growth stage) has unique effect on crop yield and the effect of water deficit at one growth stage is independent of the others, but they have a multiplicative or additive effect on the total crop yield. That is, crop water deficit in two or more periods may reduce yield in a multiplicative or additive manner (Taskiris, 1982).

For this study, two of the multiplicative types of crop yield models: Jensen (1968) and Minhas et al (1974); and two of the additive models: Stewart et al (1977) and Bras and Cordova (1981) were considered. In these models, grain yield were related to evapotranspiration in each case.

2.6.1 The Multiplicative Models

Jensen (1968) developed a crop production function which divided the crop growing season into stages, with evapotranspiration deficit in each stage having a unique effect on yield. The function expresses relative grain yield (ratio of actual grain yield, Ya,to maximum yield, Ym) as a function of relative evapotranspiration (actual evapotranspiration ETa divided by maximum evapotranspiration, ETm). The expression is given as (Jensen, 1968)

$$\frac{y_a}{y_m} = \prod_{i=1}^{n} \left(\frac{ETa}{ETm}\right)_i^{\lambda_i} \qquad \ldots\ldots\ldots\ldots 2.6$$

Where: λ = the relative sensitivity of the crop to water stress in the growth stage and is a parameter to be estimated.

n = the number of growth stages considered,

Π = multiplicative sign, and the other terms are as defined previously.

Minhas et al 's (1974) production function is also based on relative evapotranspiration, given as ; (Minhas et al, 1974)

$$\frac{ya}{ym} = \prod_{i=1}^{n} \left[1.0 - \left(1.0 - \frac{ETa}{ETm} \right)_i \right]^{b_i} \quad \ldots\ldots\ldots\ldots 2.7$$

in which is b_i the parameter to be estimated, defined as the relative sensitivity factor of the crop to water stress in the ith growth state, and the other terms as previously defined.

For the multiplicative expression, the crop yield becomes Zero if evapotranspiration becomes Zero at any growth stage.

2.6.2. The Additive Models.

The Bras and Cordova's (1981) model is given by the expression

$$\frac{ya}{ym} = \sum_{i=1}^{n} A_i \left(\frac{ETa}{ETm} \right)_i \quad \ldots\ldots\ldots 2.8$$

in which A_i is the crop sensitivity parameter to be estimated, and the other terms as previously defined.

Stewart et al (1977) gave a generalised crop production function which relate dry matter yield to total seasonal evapotranspiration with no reference to irrigation timing relative to the crop growth stage, expressed as (Stewart et al., 1977).

$$\left(1 - \frac{DMa}{DMm} \right) = \beta_a \left(1 - \frac{ETa}{ETm} \right) \quad \ldots\ldots\ldots 2.9$$

in which β_a is a coefficient known as the yield response factor or yield

reduction ratio describing the sensitivity of the crop to moisture stress applied; DMa is the actual dry matter yield; DMm is the maximum dry matter yield, and the other terms are as previously defined.

Equation 2.9 was described by Hanks and Hill (1980) as a simple model and could be used for many situations where timing of irrigation is not practically important, and can be applied directly where total dry matter is the desired product. For grain production, irrigation timing, relative to crop growth stages is very important. Consequently, Eq.2.9. was modified by Stewart et al. (1977) to allow for growth stages - evapotranspiration deficit effects. The modified expression, as sited by Stegman et al (1980b) is:

$$(1 - \frac{ya}{ym}) = \sum \beta_i (\frac{ETm_i - ETa_i}{ETm}) \qquad \ldots\ldots 2.10$$

where: β_i = yield sensitivity factor of evapotranspiration deficit in growth stage i

ET = actual evapotranspiration at growth stage i

Etm_i = maximum evapotranspiration at growth stage i

Etm = total maximum evapotranspiration accumulated during the growing season of the crop, Ya and Ym are as previously defined.

Equation 2.9 is developed for predicting dry matter yield while Eq.2.10 is to be used for grain yield. However, Hanks and Hill (1980) suggested that Eq.2.9 can also be used for grain yield prediction.

In the work presented herein, Eqs. 2.6, 2.7, 2.9, and 2.10 were studied for grain yield and Eq. 2.9 for dry matter yield. The feasibility of using Eq. 2.9

for grain yield analysis was also examined.

2.7. Water Use Efficiency (WUE)

Water use efficiency is defined as the mass ratio of crop yield to water use (Viet, 1962). The yield can be characterised by the end product of a plant such as grain, seed or lint, or by the vegetative component or a combination of these representing the total biological yield, while the water use can be characterised by transpiration or evapotranspiration.

The expression is given as:

$$WuE = \frac{y}{ET} \quad \ldots\ldots\ldots 2.11$$

in which Y is crop yield(kg/ha)and ET is evapotranspiration in mm.

Water use efficiency can be increased either by increasing the numerator or decreasing the denominator. Hillel and Guron (1973) argued that it appears more promising to attempt to increase WUE by increasing crop yield than by decreasing evapotranspiration since plant growing in the field are subject to an externally imposed evaporative demand. Plant may curtail transpiration when the supply of soil water becomes limiting, but curtailing transpiration often entails restricting growth and subjecting the plants to stress during the growing period. The water stress may be temporary but can still reduce production, whereas the maintenance of a relatively moist root zone by frequent irrigation at a rate nearly commensurate with potential evapotranspiration can increase crop production, perhaps, even disproportionately to the increased water use, thus, increasing

WUE. However, Howell and Hiller(1975) and Stewart et al (1983) argued that Hillel and Guron's (1973) statement is only valid for well-watered crop regimes but does not fully explore the possible implications of limited irrigation regions of short and or costly water supplies. Limited irrigation will presumably decrease crop, therefore, for an area where land is not limited but water is, emphasis should be given to developing systems that reduces all losses other than transpiration which is possible with less frequent of irrigation.

2.8. Experimental Design Approach.

According to Stegman (1983), two types of experimental designs have been used in the past decade to study irrigation scheduling effects on seed or grain harvested crops. Only the design used in the work reported herein is reviewed.

In this design the crop growing season may be divided into stages, such as: vegetative, flowering, pollination, and seed filling periods. Water stress is imposed in a given period by withholding irrigation (symbolised by letter "O") either entirely or to a quantified stress level before relief. Irrigation or maintenance of non or low stress level before or after the stress period (symbolised by letter "I"). Irrigation treatments therefore, may range from full irrigation, that is maintenance of maximum evapotranspiration rate, in all growth stages symbolised by "III" to a non-irrigated or all growth stages stress treatments symbolised by "OOO" and all combinations such as OII, OOI, OIO and others in between. Stress imposed is normally limited to one growth period with

irrigation withheld either entirely or until a quantified degree of moisture deficit occurs, usually measured as the evapotranspiration deficit relative to the evapotranspiration of the non-stress treatment, and the maximum seasonal yield (Ym) is usually associated with the scheduling treatment III which also accumulates the maximum seasonal evapotranspiration (ETm) (Stegman et al, 1980; Stegman; 1983; Bungwon, 1993). In the study reported herein, the above experimental design approach was used with the growing season of the wheat crop divided into four growth stages: stem elongation to booting initiation; booting to full heading; flowering to milk dough development; and, soft dough to hard dough stages.

3. MATERIALS AND METHODS

3.1 Introduction

The experiment was conducted at the Institute for Agricultural Research (I.A.R.) irrigation farm in Samaru, Zaria, which is on latitude 11° 11'N, longitute 7°37'E, and at an altitude 675m above mean sea level, during the cool, dry harmattan season between November 1995 and March 1996.

3.2 Climatic Condition of the Experiment Site:

The climate of Samaru is described as dry, sub-humid with a severe deficit in rainfall from October to May and a surplus from June to September with an average annual rainfall of 1000mm (Kowal and Andrew, 1973). The average incoming solar radiation ranges from 16.5 MJ/m^2/day in August to 20.9 MJ/m^2/day in March. The range in the solar radiation implies that light and temperature do not greatly limit potential crop production at any time of the year (Kowal and Andrew, 1973), The average mean daily temperature from November to Mid-February is generally low and ranges from 19°C to 23°C, while for the remaining months of the year, the daily temperature ranges between 23° C and 32°C. This temperature regime throughout the year is suitable for growing tropical crops such as maize, sorghum, rice, groundnut and others, under rain-fed conditions, and subtropical crops such as wheat, tomato, onion, cabbage and other during the irrigation season of November to April.

The meteorological data for the period of the study was obtained from the Institute for Agricultural Research meteorological station located 150m away from

the experimental plots and given in Table 3.1. Also included in the table is the average mean monthly values for 5 years (1989 to 1994). The result shows that the weather condition for the season did not differ widely from the previous years.

Table 3.1 Meterological Data during the Crop Growing Season.

	Mean monthly values			
	Dec.	Jan.	Feb.	March
Maximum temperature (°C)	29.6 (28.9)	28.9 (27.3)	31.9 (30.9)	33.6 (33.4)
Minimum temperature (°C)	11.1 (12.2)	13.5 (13.1)	15.7 (16.8)	17.2 (16.4)
Wind speed (km/hr)	197.5 (195.1)	127.4 (132.4)	138.1 (144.0)	130.1 (133.1)
Relative humidity (%)	37.0 (38.0)	22.1 (22.4)	17.8 (15.5)	15.5 (14.3)
Pan evaporation (mm/day)	10.8 (10.8)	9.3 (9.0)	10.0 (11.7)	11.1 (12.4)

The figure in bracket is the average for a period of five years (1989 - 1994).

3.3. Soil Condition of the Experimental Site

The soil of Samaru has been classified as a leached ferruginous tropical soil freely draining with its surface covered by fine aeolian materials with an upper 300mm of surface soil capable of holding a large amount of available water of between 60-300mm (Kowal and Andrew, 1973). The soil is described by Kowal (1968) as a "loess plant" formed by the addition of fine drift materials into a sedentary soil derived from cambrian basement complex formation and have a high proportion of fine sand at or near the surface. The clay content increases

with depth and consequently the water available for plant use decreases and becomes increasingly difficult to be extracted by the plant. The soil is underlain by a basement complex rock resistant to weathering, with a thin and clayey mantle of weathering material, which can retain large quantities of water (Kowal and Andrew, 1973). It is also characterised by high capillary conductivity with low infiltration rate and high run off. Table 3.2 and 3.3 show some physical and chemical properties of the soil in the experimental plot, respectively.

3.4 Field Preparation and Layout

A land area of 800m^2 was ploughed and harrowed, and divided into three blocks laid along the general slope of the field in order to ensure as much homogenous soil conditions as possible within the block. Each block was divided into fourteen basins, corresponding to the number of treatment which were then laid in two rows of seven basins each. The basins were spaced 1.0m apart and the blocks (replications) 1.5m apart to create a buffer zone between basins and blocks in order to reduce possible seepage of water from one basin to another as a result of lateral movement of water. Each row of basins was served water through a furrow running along the slope adjacent the basins and a basin is opened at one point to allow water to flow in rapidly until it is adequately ponded, after which it is closed. The field layout is as shown in Fig 3.1.

Table 3.2. Physical Properties of Soil in the Experimental Plot.

	Soil suction x 10^2 kPa						Bulk density g/cm^3	Soil text. class
	0.1	1.0	3.0	5.0	10.0	15.0		
Depth(mm)	% Moisture content (dry weight)							
0 - 150	14.0	7.4	6.7	3.6	3.4	3.1	1.58	loam
150 - 300	12.0	10.7	10.0	6.8	6.2	4.5	1.60	clay loam
300 - 450	16.9	14.7	14.3	12.9	10.3	8.7	1.61	clay loam
450 - 600	21.4	19.2	15.0	14.5	13.3	10.0	1.62	clay

Table 3.3. Chemical Properties of the Soil in the Experimental Plot.

p^H in water	5.60
p^H in 0.0lm $cacl_2$	4.85
% organic carbon	0.50
Available phosphorus (mg/l)	4.73
% total Nitrogen	0.07
Exchangeable cation (Meg/100g of soil)	
Ca^{++}(mg/l)	3.03
Mg^{++} (mg/l)	0.02
K^+ (mg/l)	0.26
Na^+ (mg/l)	0.12
CEC(%)	5.24

Source: Nwokeocha (1995)

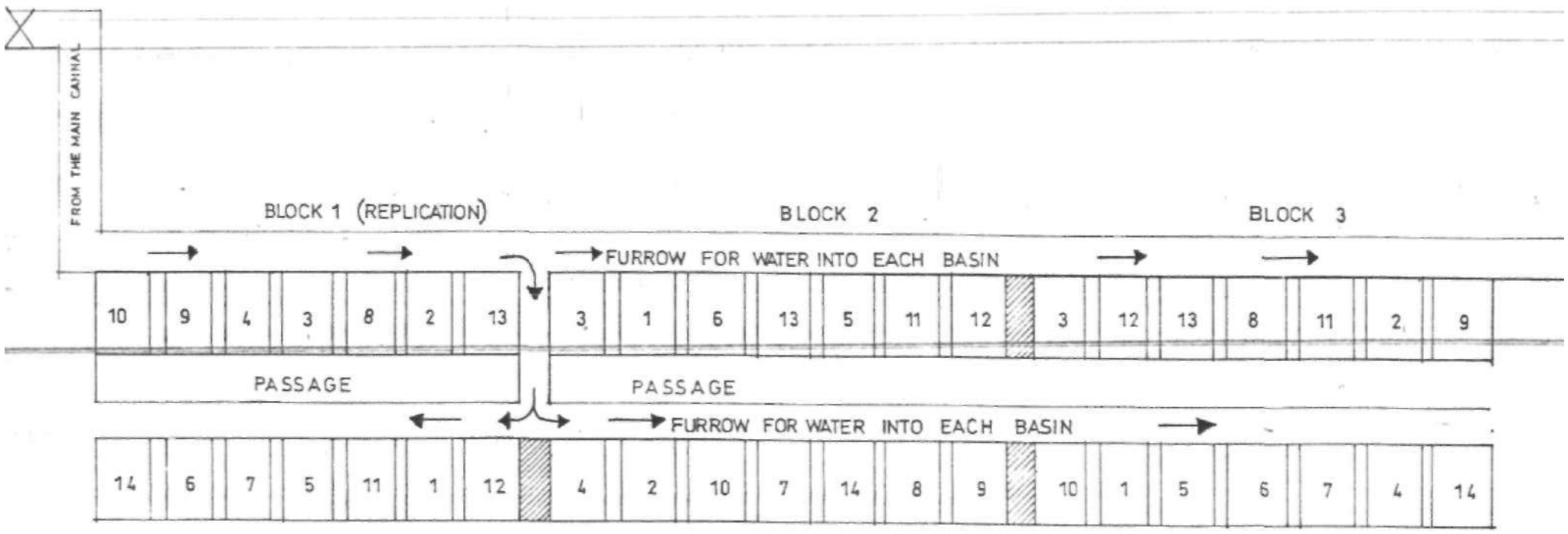


FIG. 3.1: Layout of The Experimental plots.
(Numbers indicate the treatment label. Not drawn to scale)

3.4.1 Field Operations

The basins were seeded to wheat (Triticum aestivum L. CV. Sete ceros) on 25th November, 1995, by hand- drilling in rows at a rate of 100kg/ha. A pre-planting irrigation was done two days before planting to give a wet soil regime to enhance seed germination. The spacing between planting rows was 250mm and a total of eight rows per basin were planted. The plant population per row was approximately uniform as was observed. Compound fertilizer (NPK 15:15:15) was applied at a rate of 50kg/ha of Nitrogen, phosphorus and potassium at planting and NPK 25:10:10 was used for top dressing four week after planting to raise the level of Nitrogen applied to 120kg/ha in line with recommended practice (Bungwon, 1993). Weeding operation was done at three weeks after germination and thereafter, no weed was found growing within the basin except on the basin embarkments and these were removed from time to time.

3.5 Experimental Treatments

A total of fourteen treatments were considered in the study. The treatment variable being the time of water application only. All agronomic practices that were needed for good crop growth and yield were observed as practicable as possible for all the treatments and replications. The treatments were replicated three times in a randomized block design. After germination, a 7-day irrigation interval was observed until the crops were fully established at 30 days after planting. thereafter, the various moisture stress treatments were imposed. The

moisture stress treatments used for this study were related to four growth stages of the crop given in Table 3.4.

Table 3.4. Description of Growth Stages Considered in the Experiment.

Growth Stage	Description	Period (days after planting)
I	Stem elongation to booting initiation	30 - 44
II	Full booting to full heading	45 - 58
III	Flowering to milk-dough development	59 - 72
IV	Soft dough to hard dough development	73 - 86

The divisions and description of these growth stage were closely related to those suggested by Zadok et al., (1974) and Yayock and Kumar, (1980). Stage I coincides with Zadok et al's (1974) stage 3 and half of stage 4; and Yayock and Kumar's (1980) stages 3.4 to 4.2. Stage II coincides with the other half of stage 4 and stage 5 of Zadok et al (1974), and also with Yayock and Kumar's (1980) stages 4.5 to 5.5. Stage III coincides with stages 6 and 7 of Zadok et al (1974) and Yayock and Kumar's (1980) stages 6.1 to 7.2. Stage IV coincides with Zadok et al's (1974) stages 8 and 9, and Yayock and Kumar's (1980) 8.1 to 9.0. It should be pointed out that the periods, that is, days after planting, of each stage did not completely coincide with those given by Yayock and Kumar (1980),

but were very close to those of Zadok et al (1974).

The treatment pattern followed the experimental design approach reviewed in Section 2.7. It involved irrigating at 7-day interval after the crop establishment; which is the recommended irrigation interval for wheat in Samaru (Chari, 1980);for all the growth stages except at the particular growth stage at which stress treatment was imposed. The stress was imposed by withholding irrigation for additional days in excess of the regular 7-day irrigation interval. It was expected that by withholding irrigation from the crop at any of the stages for a given number of days in excess of the regular irrigation intervals, while the control treatment was irrigated, an evapotranspiration deficit will occur in the stressed plots resulting to moisture stress which could affect the crop yield. Three levels of moisture stress were considered for each of the four growth stages. The three levels were: Irrigation withheld 4 days, 7 days and 9 days in excess of the 7-day irrigation interval, and labelled "a", "b" and "c", respectively at the growth stages I, II, III and IV. In the dry treatment (labelled 14) the crop was stressed to level b in all the four growth stages. This was to enable us compare the effect of single stress and stress throughout the growing season on the crop yield. Table 3.5 gives the treatments' description.

After the days of stress were over, the crops were thereafter irrigated at 7-day intervals, for the rest of the growing season. Each treatment was stressed once except treatment 14 that was stressed to level "b" at all four stages, and was labelled dry treatment. The control treatment was irrigated at 7-day

Table 3.5 Description of the Imposed Treatment

Growth Stage	Treatment Label	Treatment Description
Control	1	Regular 7-day irrigation interval for the season
I	2	Irrigation withheld once to level "a" at stage I only
	3	Irrigation withheld once to level "b" at stage I only
	4	Irrigation withheld once to level "c" at stage I only
	5	Irrigation withheld once to level "a" at stage II only
II	6	Irrigation withheld once to level "b" at stage II only
	7	Irrigation withheld once to level "c" at stage II only
	8	Irrigation withheld once to level "a" at stage III only
III	9	Irrigation withheld once to level "b" at stage III only
	10	Irrigation withheld once to level "c" at stage III only
	11	Irrigation withheld once to level "a" at stage IV only
IV	12	Irrigation withheld once to level "b" at stage IV only
	13	Irrigation withheld once to level "c" at stage IV only
Dry treat.	14	Irrigation withheld to level "b" at all four stages.

interval for the entire growing season.

3.6 Irrigation Method

Irrigation was by check basin method. A basin to be irrigated was opened at a point by breaking the basin embarkment and water allowed in until the basin was adequately ponded, after which the basin was closed by replacing the soil taken out of the embarkment. The quantity of water applied at each irrigation could not be measured due to lack of water measuring instrument. To ensure that crops were not under irrigated at each irrigation the basins were always ponded such that the soil moisture level was raised to field capacity as indicated by comparing moisture content obtained two days after irrigation with a Laboratory-determined moisture content at a soil suction of 30.0kPa using the pressure plate apparatus. Irrigation was cut off 90 days after planting to allow the crops to dry in readiness for harvest which was done 105 days after planting.

3.7 Soil Moisture Determination

Soil moisture was monitored throughout the irrigation season for each treatment by collecting soil samples for soil moisture determination two days after irrigation and just before the next irrigation. Soil samples were collected from a soil depth of 0 - 600mm at an incremental depths of 150mm in two replications for each treatment using an auger, and were dried in the oven at 105°c for 24 hours to determine the soil moisture content. The difference in moisture contents between the two sampling periods was regarded as the moisture use, that is,

evapotranspiration, by the crop for that period in line with the water budget method described in section 2.4.2. It was assumed that drainage was negligible after the soil has attained the field capacity. Moisture change, therefore was principally attributed to evapotranspiration. Since the crop used water for the two days before the soil sampling was done, evapotranspiration for these two days was assumed to be at maximum since soil water was adequate. Thus, the value of evapotranspiration for the two days estimated from open pan evaporation data was added to the measured evapotranspiration to obtain the total moisture used for each period.

3.8 Determination of Yields and Harvest Index.

Harvesting was done from 6th to 9th March, 1996. The total above - ground dry matter was cut manually using a sickle, from an area of 2.5 x 1.0m^2 which consisted of the four middle rows of each basin, so as to eliminate error due to border effects. Harvest from the four rows were tied together and weighed to obtain the dry matter yield, and then threshed to obtain the grain. Harvest Index (HI) for each treatment was calculated using Eq.2.1.

3.9. Yield - Water Use Relationships.

The relationship between grain yield and seasonal evapotranspiration; and dry matter yield and seasonal evapotranspiration w established using the field data obtained as explained in section 3.7 and 3.8. Using the least sqaures method, the best fit curves were drawn to establish linear relationships between grain yield and seasonal evapotranspiration; and between dry matter yield and seasonal

evapotranspiration. The relative yields and relative evapotranspiration relationships were also established using the least square method. The yield from the control treatment and its seasonal evapotranspiration was taken to be maximum yield (Ym) and maximum evapotranspiration (ETm), respectively.

3.10 Models Parameters Determination.

The parameters to be estimated in each of the model under study is the stress sensitivity factors for the four growth stages considered in this work.The relative yield (Ya/Ym) and the relative evapotranspiration (Eta/ETm) terms of the model expressions were obtained from the yields and evapotranspiration data measured as explained in sections 3.7 and 3.8. The stress sensitivity factor for each of the growth stages for each model were obtained by using the multiple linear regression technique. The multiplicative type model equations were first transformed to logarithmic equations for the regression analyses. Data from eight treatments selected randomly were taken at two treatment levels per growth stage, in addition to the control treatment and used to estimate the sensitivity parameters. The remaining data were then used to test the applicability and accuracy of the estimated parameters in predicting grain yield.

The coefficient of Stewart et al's (1977) expression (Eq. 2.9) were also determined for dry matter production and for grain yield by plotting the relative yield reduction, (1-Ya/Ym) versus seasonal relative evapotranspiration deficit, (1-ETa/ETm) on a linear graph paper and by using the least squares method, the line of best-fit was established. The slope of the fitted line is the yield response

factor (Doorenbos and Kassam, 1979). In the same manner, the eight randomly selected treatments used in estimating the sensitivity parameters of the other models were also used, and the results obtained were tested using the relative evapotranspiration deficit terms of the other treatments to see how effectively closely the expression can predict relative yields of dry matter and grains. Field -measured relative yields and the models estimated relative yields were then compared at 0.05 level of significance using the statistical "t" test.

3.11 Water Use Efficiency (WUE)

Water use efficiencies were calculated for grain using Eq.2.11.Grains yield were expressed in Kg/ha and the seasonal evapotranspiration expressed in mm. thus, water use efficiency was obtained kg/ha-mm.

4. RESULTS AND DISCUSSION

4.1 Introduction.

The relationship between crop yield and water use is very unique. When climatic and agronomic conditions are adequate, crop yield completely depends on the amount of water available for use by the crops. According to Doorenbos and Kassam (1979), when economic conditions do not restrict crop production, and in a constraint -free condition , crop yield is at maximum, when full water requirements are met. When water supply does not meet crop water requirement, actual evapotranspiration (ETa) will fall below maximum evapotranspiration (ETm) resulting o a water deficit in plant which may develop to a point where crop growth and yield are adversely affected. The effect of the magnitude and the timing of occurrence of water deficit on crop growth and yield is therefore of major importance in scheduling available but limited water supply for the growing period of the crop and in determining the priority of water supply amongst different crops during the growing season.

Relationships between crop yields (both grain and dry matter yields) and seasonal evapotranspiration for wheat in Samaru, Zaria, under conditions of moisture stress caused by evapotranspiration deficits at four growth stages of the crop are discussed below.

4.2. Crop Water use

Table. 4.1. shows the water used by crop as measured on the field using

Table 4.1 Growth Stages and Seasonal Evapotranspiration(mm) Measured on the Experimental Plots.

Treat/-ment	Growth Stages: / Stress/-level	I	II	III	IV			Seasonal ET
		Days after Planting						
		1-29	30-44	45-58	59-72	73-86	87-93	1-93
1	Control	41.4	63.1	92.0[x]	99.1[x]	83.2	29.7	409
2	a	37.3	56.1[y]	86.3	96.1	82.8	29.9	389
3	b	39.8	48.5[y]	85.5	98.4	81.0	29.5	383
4	c	40.2	45.5[y]	85.0	92.2	81.6	30.9	375
5	a	43.3	64.0[x]	72.3[y]	90.5	82.2	34.0	387
6	b	56.0	61.8	60.7[y]	97.4	82.4	36.9	375
7	c	40.6	62.2	55.9[y]	85.8	84.0[x]	31.0	360
8	a	38.0	62.0	87.9	74.3[y]	76.0	30.7	369
9	b	37.2	61.7	87.6	61.9[y]	76.3	30.0	355
10	c	38.7	58.4	89.6	57.8[y]	70.9	34.9	350
11	a	42.1	60.0	90.0	97.1	65.2[y]	29.2	384
12	b	40.7	58.6	89.7	98.8	58.1[y]	30.0	376
13	c	38.6	63.0	87.1	89.6	52.8[y]	37.8	369
14	"b" (allstages)	45.3	46.3[y]	61.7[y]	64.7[y]	56.9[y]	15.9	291

x - heighest evapotranspiration values at the growth stage
y - evapotranspiration measured in those treatments undergoing stress at that growth stage.

the water budget method for the growth stages under consideration and for the entire season. Treatments labelled 5 and 7 recorded the highest measured evapotranspiration value at growth stage I and IV, respectively, while the control treatment labelled 1 had the highest evapotranspiration value at stages II and III. It can be observed from table 4.1 that the evapotranspiration of stressed treatments could not reach the maximum accumulated evapotranspiration of the next growth stage after the stress has been removed from them. At the stages where the water stress was severe or had severe impact on the crop, the evapotranspiration from such treatments were markedly reduced for the rest of the growing season even when the crops were adequately watered. This was particularly noticed in treatments 7 at growth stage II and treatments 8, 9, and 10 at growth stage III. This clearly shows that severe moisture stress at late vegetative and flowering growth stages will reduce crop evapotranspiration even after the stress is removed from the crops. The highest evapotranspiration amount obtained from treatment 7 at stage IV is as a result of high direct evaporation from the basins because the plant cover was markedly reduced due to tiller senescence resulting from moisture stress at stage II. The high evapotranspiration amounts recorded at 87-93 days after planting in all treatments can be attributed to direct evaporation from the basins as crops were already drying at this period.

Table 4.2 shows the growth stages and seasonal relative evapotranspiration deficits calculated using Eq.2.3. The evapotranspiration deficits indicate the degree of severity of the moisture stress at a growth stage.

Table 4.2: Growth Stages and Seasonal Relative Evapotranspiration Deficits(%).

Growth stage	Treatment	Stress level	Growth Stage ET deficit	Seasonal ET deficit
Control	1			
I	2	a	12.3	4.9
	3	b	24.3	6.3
	4	c	29.0	8.3
II	5	a	21.5	5.4
	6	b	34.0	8.3
	7	c	39.3	12.0
III	8	a	25.1	9.3
	9	b	37.6	13.2
	10	c	41.7	14.3
IV	11	a	22.4	6.0
	12	b	30.9	8.7
	13	c	37.2	9.7
Dry treatment	14*	bI	27.7	28.3
		bII	32.9	
		bIII	34.7	
		bIV	32.3	

*Treatment 14 was stressed at level "b" in all the four growth stage.

It can be observed from Table 4.2 that the treatments with the same stress, level that is, number of days in which irrigation was withheld in excess of the regular irrigation interval, at different growth stages had different evapotranspiration deficit. Sesonal evapotranspiration deficit rose to a peak value of 14.3 % at stage III and dropped again to 6.0% at growth stages IV. The seasonal evapotranspiration deficit for the dry treatment was 28.3%. It can be observed that even the Evapotranspiration deficit at stress level "a" at growth stage III was higher than that of stress level"b" at stage IV, and levels "b" and "c" of stages II. Generally, higher evapotranspiration deficits were recorded at growth stage III because the crop peak consumptive use is at this stage, so that when irrigation is withheld, a sharp drop in evaportranspiration compare to the maximum results, thus making that growth stage more critical to moisture stress than others.

4.3. Grain and Dry Matter Yields

Tables 4.3 and 4.4 show the grain yield and dry matter yield for each replication and the average yield for each treatment, respectively, and Table 4.5 and 4.6 shows the analysis of variance for the mean grain and dry matter yields respectively. Table 4.5 shows that the grain yield mean differences of the growth stages were highly significant, and the mean differences of the stress levels were only significant at 0.05 level of siginificance. These results show that the variation in grain yield was highly influenced by the growth stages at which stress

Table 4.3. Grain Yield Obtained from the Experiment.

Growth stage	Treatment	Replication Yield ($g/2.5m^2$)			Average Yield	
		A	B	C	$g/2.5m^2$	t/ha
Control	1	691.6	701.6	631.0	674.7	2.70
	2	638.6	596.2	638.6	624.4	2.50
I	3	643.0	617.6	587.1	615.9	2.46
	4	624.2	622.4	590.0	612.2	2.45
	5	575.0	635.4	647.0	619.1	2.48
II	6	623.8	558.0	575.0	585.6	2.34
	7	542.0	448.4	553.0	516.2	2.07
	8	551.0	518.8	509.8	526.5	2.11
III	9	478.5	546.0	478.5	501.0	2.00
	10	542.5	431.4	514.3	496.1	1.98
	11	605.5	600.5	645.8	617.4	2.47
IV	12	553.7	620.7	618.7	597.7	2.39
	13	568.7	612.6	596.2	592.5	2.37
	14	427.5	377.4	378.0	394.1	1.58
Dry Treat.						

Table 4.4: Dry Matter Yield Obtained from the Experiment.

Growth Stages	Treatment	Replication Yields (kg/2.5m²)			Average Yield	
		A	B	C	kg/2.5m²	t/ha
control	1	1.85	2.20	1.80	1.95	7.80
	2	1.70	1.80	1.70	1.73	6.92
I	3	1.70	1.90	1.70	1.77	7.08
	4	1.70	1.80	1.60	1.70	6.80
II	5	1.75	1.80	1.85	1.80	7.20
	6	1.65	1.75	1.55	1.65	6.60
	7	1.50	1.40	1.60	1.50	6.00
III	8	1.80	1.60	1.70	1.70	6.80
	9	1.40	1.75	1.65	1.60	6.40
	10	1.40	1.70	1.70	1.60	6.40
IV	11	1.80	1.90	1.90	1.87	7.48
	12	1.65	1.70	1.80	1.72	6.88
	13	1.75	1.75	1.70	1.73	6.92
	14	1.30	1.25	1.25	1.27	5.08

Table 4.5 Analysis of Variance For Grain Yield

Source	Df	SS	MSS	F	Remark
Replication	2	48.8	24.4	0.02	NS
Growth Stage	3	63970.5	21323.5	12.8	**
Stress Level	2	12036.6	6018.3	3.60	*
Interaction btwn Growth stage and Stress level	6	8585.9	1431.0	0.9	NS
Contol treatment VS Sress treat-ments	1	27426.8	27426.8	16.5	**
Dry treatment VS Stressed treat-ment	1	90636.5	90636.5	54.4	**
Error	26	43319.4	1666.2		
	41				

Mean Ranking:

Growth Stage	Stress level
I_x +	a_x
II_y	b_{xy}
III_z	c_y
Iv_{xy}	

NS = Non significant

** = Highly significant

* = Significant at 0.05 level

+ = Growth stages or stress level with the same letter are not significant.

Table 4.6 Analysis of Variance For Dry Matter Yield.

Source	Df	SS	MSS	F	Remark
Replication	2	0.06	0.03	3.00	NS
Growth Stage	3	0.12	0.04	4.00	*
Stress Level	2	0.12	0.06	6.00	**
Interaction btwn Growth stage and Stress level	6	0.08	0.01	1.00	NS
Contol treatment VS Sress treatments	1	0.18	0.18	18.00	**
Dry treatment VS Stressed treatment	1	0.51	0.51	51.0	.*
Error	26	0.34			
	41				

Mean Ranking: Growth Stage

I_x +
Ii_y
III_y
Iv_x

Stress level

a_x
b_y
c_z

NS = Non significant
** = Highly significant
* = Significant at 0.05 level
+ = Growth stages or stress level with the same letter are not significant.

was imposed, and fairly influenced by the degree or the severity of the stress imposed. The mean ranking for the growth stages shows that the mean grain yield at growth stage I, that is, stem elongation to booting initiation was not significantly different from that of stage IV, that is, soft dough to hard dough development, but was significantly different from stages II and III. The mean yield for stage III was however significantly different from the other three growth stages. The mean ranking for the stress level shows that the mean yield for stress level "a" was not significantly different from that of stress level "b", but was significantly different from stress level "c".

Table 4.6 shows that the dry matter yield mean differences for the stress levels were highly significant, while the growth stages were only significant at 0.05 level of significance. This result shows that the dry matter yield was highly influenced by the degree of stress and fairly by the growth stage. The dominating influence of the stress level over the dry matter yield can best be explained in the light of the fact that at any growth stage severe stress can either suppress tillering, reduce number of effective tillers or cause tiller/stem senecence, thus reducing dry matter yield.

Table 4.7 shows the average yields (t/ha), percent grain yield reduction (GyR); percent dry matter yield reduction (DMR); and the Harvest Index(HI) for each treatment. Grain yield reduction was less than 10% for the three levels of moisture stress at growth stage I and for stress level "a" at growth stages II and IV. However, moisture stress level "a" at stage III resulted to a 22% yield loss.

Table 4.7: Percent Yield Reduction and Harvest Index(HI)

Growth stage	Treatment	stress level	% SETd	G/Y , t/ha	DMY. t/ha	HI	GYR %	DMR %
control *	1			2.70	7.80	0.35		
I	2	a	4.9	2.50	6.90	0.36	7.4	11.5
	3	b	6.3	2.46	7.08	0.35	8.9	10.0
	4	c	8.3	2.45	6.80	0.36	9.3	12.8
II	5	a	5.4	2.48	7.20	0.34	8.2	7.7
	6	b	8.3	2.34	6.60	0.35	13.2	15.4
	7	c	12.0	2.07	6.00	0.35	23.3	23.1
III	8	a	9.3	2.11	6.80	0.31	22.0	12.8
	9	b	13.2	2.00	6.40	0.31	26.0	18.0
	10	c	14.3	1.98	6.40	0.31	26.7	18.0
IV	11	a	6.0	2.47	7.48	0.33	8.5	4.1
	12	b	8.7	2.39	6.88	0.35	11.5	11.8
	13	c	9.7	2.37	6.92	0.34	12.2	11.3
Dry Treat.	14	b (all stages	28.3	1.58	5.08	0.31	41.5	35.0

ETd = *Season ET deficit*

GY = Grain Yield

DMY = Dry matter Yield

This shows that growth stage III is more sensitive to moisture stress than the other growth stages considered in this study.

Evapotranspiration deficits of 9.3%, 13.2% and 14.3% during growth III caused grain yield reductions of 22.0%, 26.0% and 26.7%, while dry matter yield reductions were only 12.8%, 18.0% and 18.0% respectively. This implies that the evapotranspiration deficit at this stage has greater effect on grain yield than dry matter yield accumulation. The dry matter yield reductions were also observed to be higher than grain yield reduction at growth stage I, which is the early vegetative growth stage. This too implies that moisture stress imposed has greater effect on dry matter accumulation than grains at this stage.

The Harvest indices were found to range from 0.31 - 0.36 which agrees with the findings of Doorenbos and Kassam's (1979) that HI should be in the range of 0.3 - 0.4. Harvest indices for growth stage III were at the lower end of the range which indicate that less assimilate was converted to grain at this stage due to the imposed moisture stress. This is in agreement with the findings of Mcpherson (1975) that moisture stress occurrence at the reproductive stage of a crop will markedly reduce photosynthate translocation to the reproductive parts of the plant.

4.4 Crop Yields and Evapotranspiration Relationships

Table 4.8 shows the grain yield (GY), dry matter yield(DM), seasonal evapotranspiration (SET), relative grain yield (Ya/Ym), relative dry matter (DMa/DMm) and relative seasonal evapotranspiration (ETa/ETm).

Figures 4.1 a and b are the graphs of grain yield and seasonal evapotranspiration; and dry matter yield versus seasonal evapotranspiration respectively. Strong linear relationships were found between crop yields and seasonal evapotranspiration. The linear regresion equation for the dry matter versus seasonal evapotranspiration relation is given as :

$$DM = 0.0225ET - 1.56, \quad \text{--------(4.1)}$$

with a correlation coefficient "r" of 0.9365; while the regression equation for grain yield versus seasonal evapotranspiration is given as :

$$GY = 0.0102ET - 1.48, \quad \text{---------(4.2)}$$

with a correlation coefficient, r, of 0.9524

where DM = dry matter yield (t/ha)

GY = grain yield (t/ha)

ET = seasonal evapotranspiration(mm)

Table 4.8 Crop Yield and Seasonal Evapotranspiration Measured from the Field.

Growthstage	Treatment	GY t/ha	DM t/ha	SET mm)	Ya/Ym	Dma/DMm	Eta/ETm
Control	1	2.70	7.80	409.0	1.00	1.00	1.00
I	2	2.50	6.90	389.0	0.93	0.89	0.95
	3	2.46	7.08	383.0	0.91	0.91	0.94
	4	2.45	6.80	375.0	0.91	0.87	0.92
II	5	2.48	7.20	387.0	0.92	0.92	0.95
	6	2.34	6.60	375.0	0.87	0.85	0.92
	7	2.07	6.00	360.0	0.77	0.77	0.88
III	8	2.11	6.80	369.0	0.78	0.87	0.90
	9	2.00	6.40	355.0	0.74	0.82	0.87
	10	1.98	6.40	350.0	0.73	0.82	0.86
IV	11	2.47	7.48	384.0	0.92	0.96	0.94
	12	2.39	6.88	376.0	0.89	0.88	0.92
	13	2.37	6.92	369.0	0.88	0.89	0.90
Dry treatment	14	1.58	5.08	291.0	0.59	0.65	0.71

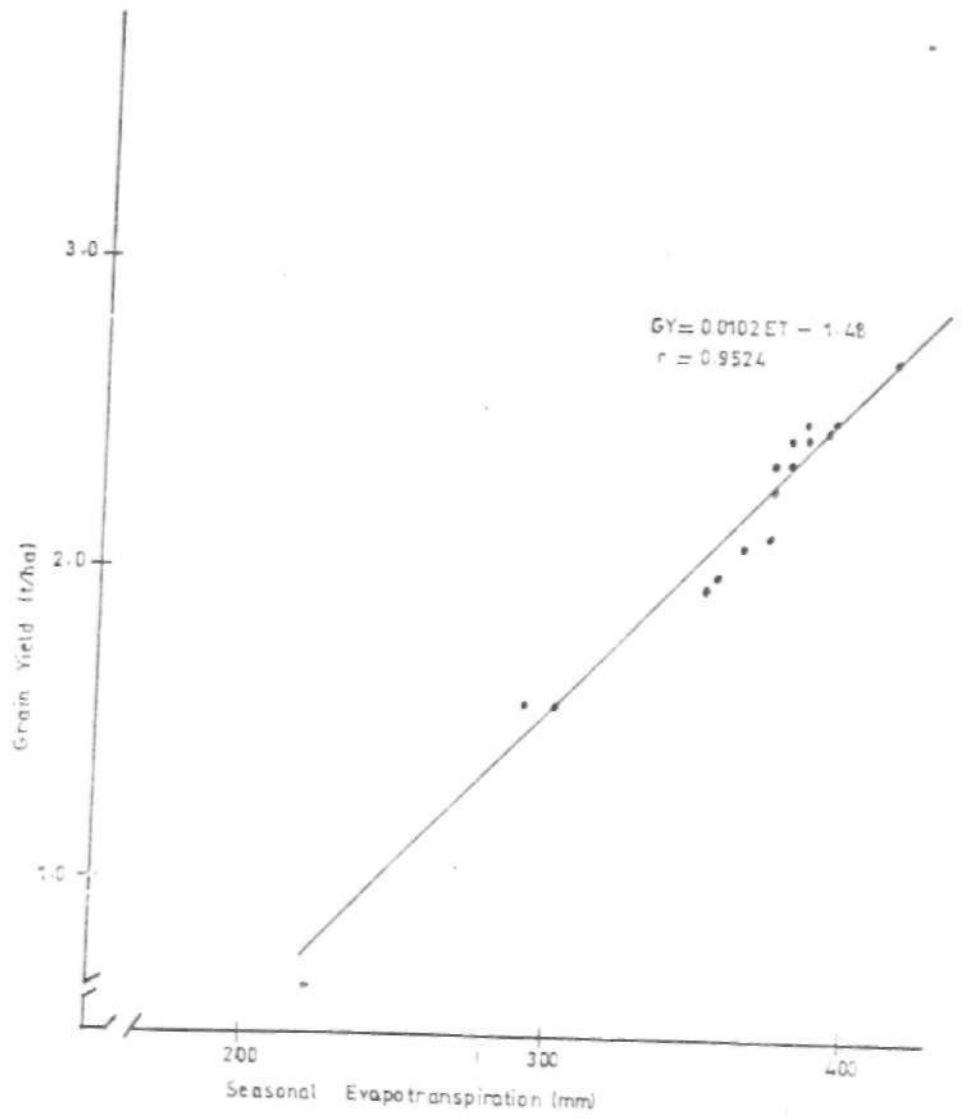


FIG. 4.1a: Grain Yield vs Seasonal Evapotranspiration.

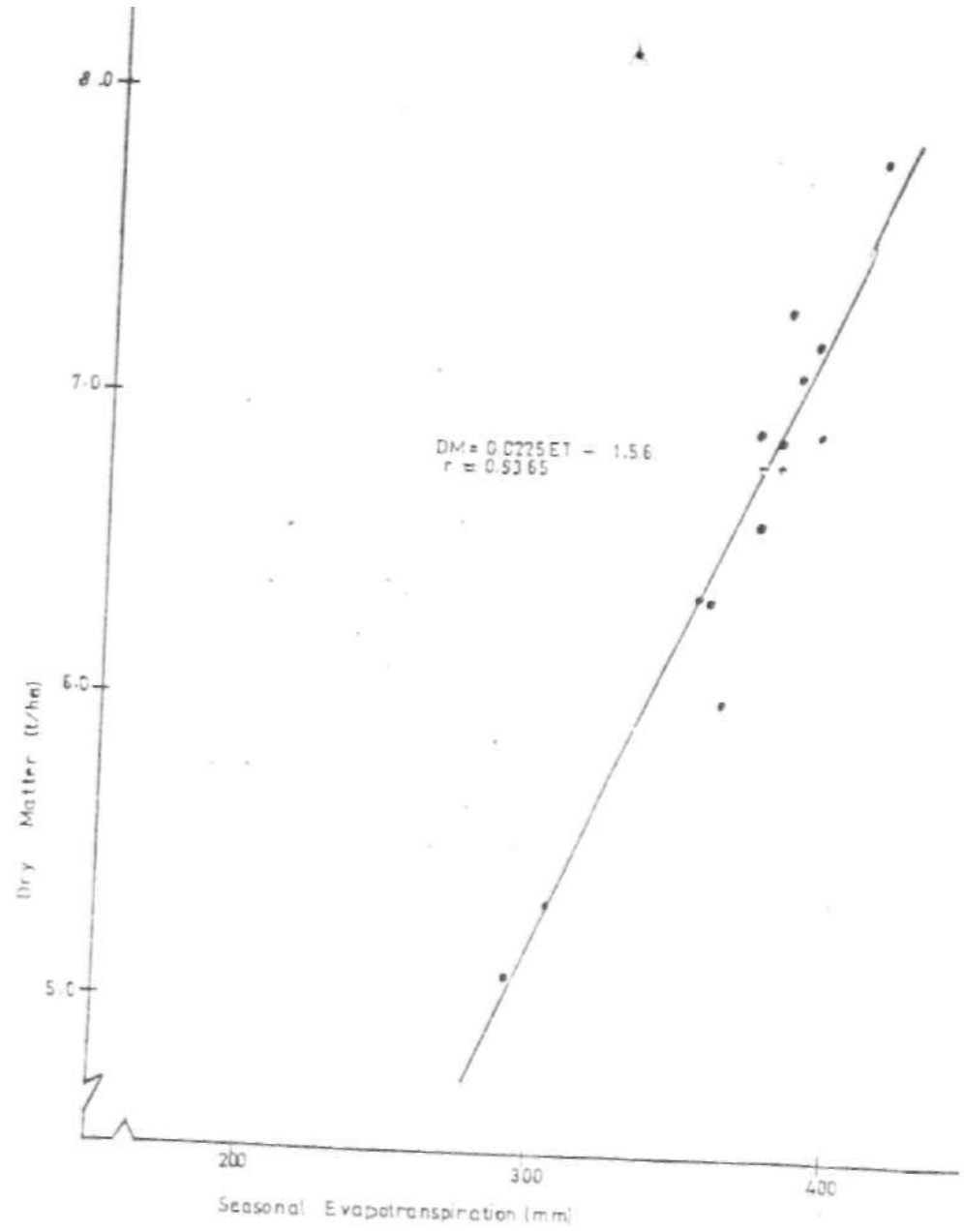


FIG 4.1b : Dry Matter Yield vs Seasonal Evapotranspiration.

Equation 4.1 reveals that an evapotranspiration (ET) threshold of 69.3mm is required to initiate a dry matter yield, and from Eq.4.2, an evapotranspiration (ET) threshold of 145 mm is required to initiate grain yield. This implies that though dry matter and grain yield will rise linearly with evapotranspiration, there is a distinct intercept or threshold value of evapotranspiration below which production is negligible. Evapotranspiration amount of 69mm is found to be 17% of the total maximum evapotranspiration of the adequately irrigated treatment while the 145 mm ET threshold required for first grain yield increment is 35% of the 409mm average evapotranspiration of the adequately irrigated treatment. The 35% value compares favourably with 30% of the maximum evapotranspiration reported by Howell (1980) for irrigated wheat based on data from Bushland, Texas, 1956-1959.

- The strong linear relationship found between crop yields (grain and dry matter) and seasonal evapotranspiration, indicates that about 10.2 kg/ha of grain could be expected for each millimeter of evapotranspiration above the threshold value of 145mm, and a dry matter yield of 22.5kg/ha could be expected for each millimeter of evapotranspiration above the threshold of 69.3mm.

Fig.4.2 a and b are the graphs of relative grain yield versus relative evapotranspiration, and relative dry matter yield versus relative evapotranspiration respectively. The regression equation for relative grain

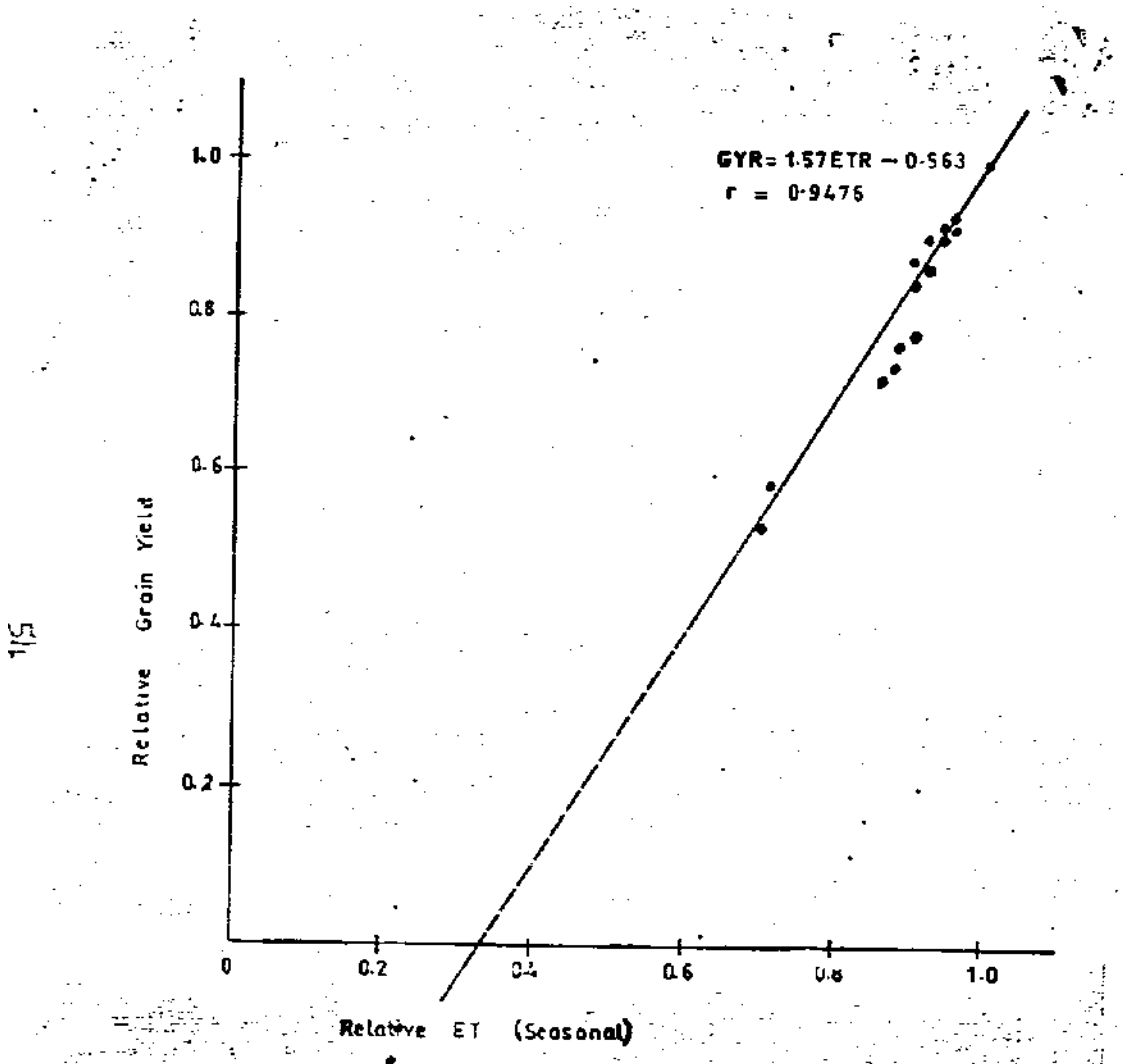


FIG. 4.2a : Relative Grain Yield vs Relative Evapotranspiration.

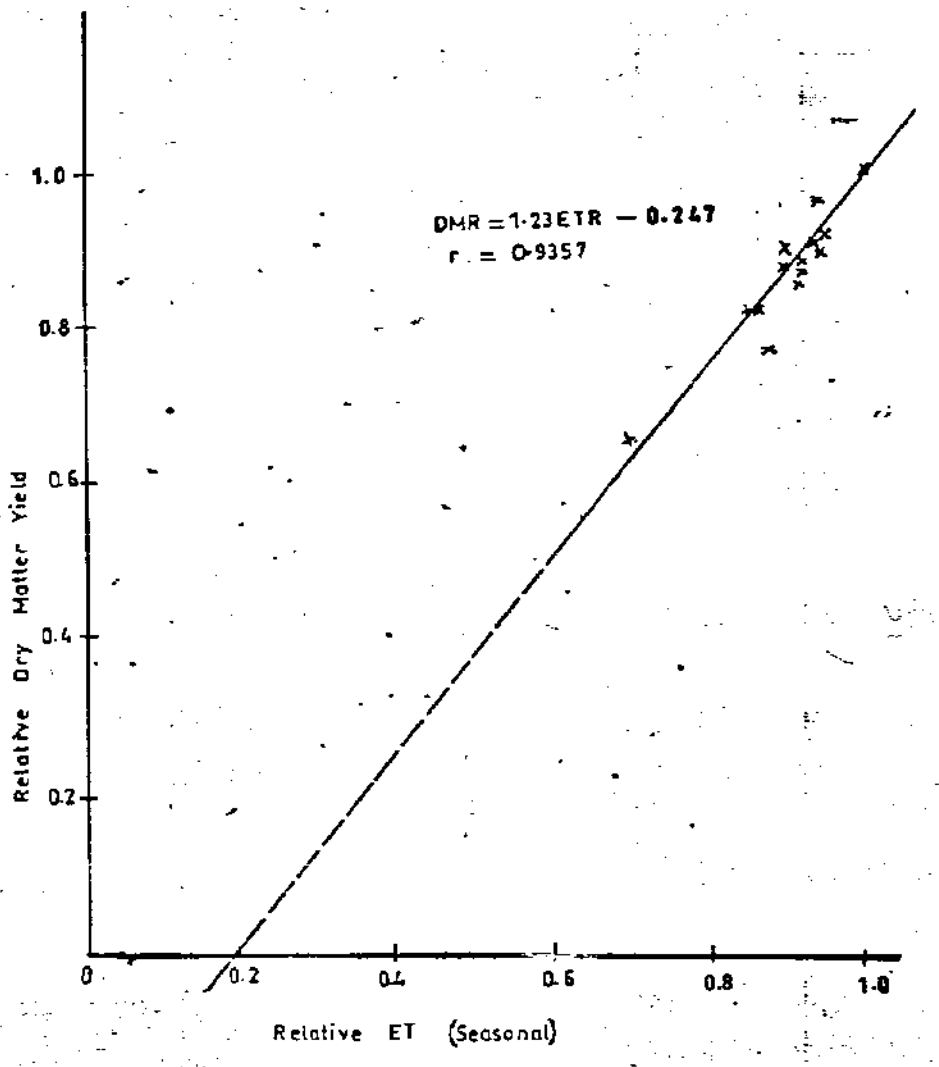


FIG. 4.2b : Relative Dry Matter Yield vs Relative Evapotranspiration.

yield versus relative evapotranspiration is given as:

$$GYR = 1.57\,ETR - 0.563 \quad \text{----(4.3)}$$

with a correlation coefficient, r of 0.9476; while the relative dry matter yield versus relative seasonal evapotranspiration relation is given as:

$$DMR = 1.23ETR - 0.247 \quad \text{----(4.4)}$$

with a correlation coefficient "r" of 0.9357

where GYR = relative grain yield (Ya/Ym)

DMR = relative dry matter yield(DMa/DMm)

ETR = relative seasonal evapotranspiration(ETa/ETm)

Equations 4.3 and 4.4 show that the relationship between the relative crop yields and relative seasonal evapotranspiration did not pass through the origin as a 1:1 fit which is an indication that the relationship between crop yield and evapotranspiration is not entirely a direct proportional relationship.This supports Hillel and Guron (1973) and Hanks et al's(1969) argument on yield and evapotranspiration relationships. The curve of the relative grain yield versus ETR intercept the ETa/ETm axis at 0.35; while that of the dry matter yield intercept the ETa/ETm axis at 0.20. These values are found to be close to, and in the range of 0.25 - 0.50 given by Stegman et al(1980 b)respectively, (see section 2.5). It can therefore be concluded that the stresses imposed were easily tolerated by the dry matter, that is, stressed imposed were not too severe for dry matter production. However, the stresses imposed were extremely severe for grain production especially at the crop most sensitive growth stage.

4.5. Grain yield - Water Use Models Parameters.

Table 4.9 shows the relative grain yield and the relative evapotranspiration data at various growth stages used for evaluating the sensitivity factors of the models under consideration as explained in section 3.10. The highest evapotranspiration value in a growth stage was taken to be maximum evapotranspiration (ETm).

Table 4.10 shows the yield models' parameter (the stress sensitivity factors). The result given in Table 4.10 show the dominating influence of the growth stage III, that is, the flowering to milk dough, development on wheat grain production. This stage had higher sensitivy factors than the others. It is followed by the booting to heading stage (II),soft dough to hard dough(IV) and lastly, the stem elongation to booting initiation (I) growth stage. However, the results show that moisture stress at any of the four stages will have significant effects on grain yield. The coefficient "B_o of the multiplicative models was a "dummy regression coefficient", (Howell and Hiler,' 1975,'s term) which did not affect the resulting equation since the Bo, is approximately

Table 4.9 Relative Grain yield and Growth stages Relative ET

Treatment	Relative Yield	Growth Stages Relative ET (ETa/ETm). I	II	III	IV
1.	1.00	0.99	1.00	1.00	0.99
2.	0.93	0.88	0.94	0.97	0.98
4.	0.91	0.71	0.92	0.93	0.97
5.	0.92	1.00	0.97	0.91	0.98
7.	0.77	0.97	0.61	0.87	1.00
9.	0.74	0.97	0.95	0.62	0.91
10.	0.73	0.91	0.97	0.58	0.84
11.	0.92	0.94	0.98	0.98	0.78
12.	0.89	0.92	0.97	1.00	0.69

Table 4.10 Estimated Stress Sensitivity factors for the Models.

	Stress Sensitivity Factors					
Model	Crop Growth Stages					
	Constant	I	II	III	IV	r
Jensen (1968)	B_o	λ_1	λ_2	λ_3	λ_4	
	0.0029	0.105	0.357	0.498	0.268	0.9806
Minhas et al (1974)	B_o	b_1	b_2	b_3	b_4	
	-0.013	0.590	1.231	1.464	0.817	0.9818
Stewart et al (1977)	B_o	B_1	B_2	B_3	B_4	
	0.0098	0.748	1.625	2.232	1.461	0.9777
Bras and Cordova (1981)	A_o	A_1	A_2	A_3	A_4	
	-0324	0.145	0.403	0.471	0.320	0.9804

zero given an exponential value 1.0. Also the coefficient B_o of the Stewart et al's (1977) model is approximately Zero, thus did not affect the resulting equation. However, the coefficient 'Ao' of the Bras and Cordova's (1981) model must be included in the model expression. Table 4.11 gives the general outlook of the models expression.

4.6 Grain Yield model Predictions

Table 4:12 shows the remaining field data (relative evapotranspiration) which were used to test the accuracy and predictability of the stress sensitivity factors. Measured relative yield and model calculated relative yield results for each model are also shown.

It can be observed that each yield model simulated the field results equally well. The absolute mean difference between the measured and calculated relative yield are: Jensen: 0.002; Minhas et al: 0.034; Stewart et al: 0.008; and Bras and Cordova: 0.002. A "t" test statistical analysis was carried out between the measured relative yield and each of the model calculated relative yield. There was no significant difference between the measured and calculated relative yields at 0.05 level of significance. This indicates that each of the model adequately predicted relative grain yield and that the sensitivity factors estimated for each model are reliable. However, from the results of the absolute mean differences shown above, Jensen (1968) and Bras - Cordova (1981) models predicted closer and more accurate results, with Minhas et al (1974) been least.

Table 4.11: **Models Expressions with their sensitivity factors.**

Jensen (1968)	$\frac{Y_a}{Y_m} = (Z)_I^{0.105} \cdot (Z)_{II}^{0.357} \cdot (Z)_{III}^{0.456} \cdot (Z)_{IV}^{0.268}$
Minhas et al (1974)	$\frac{Y_a}{Y_m} = (X)_I^{0.590} \cdot (X)_{II}^{1.232} \cdot (X)_{III}^{1.464} \cdot (X)_{IV}^{0.817}$
Stewart et al(1977)	$(1-\frac{Y_a}{Y_m} = 0.748(W)_I + 1.625(W)_{II} + 2.232(W)_{III} + 1.461(W)_{IV}$
Bras and Cordova(1981)	$\frac{Y_a}{Y_m} = -0.324 + 0.145(Z)_I + 0.403(Z)_{II} + 0.471(Z)_{III} + 0.320(Z)_{IV}$

$$Z = (\frac{ETa}{ETm})$$

$$X = [1.0 - 1.0 - \frac{ETa}{ETm})^2]$$

$$W = [\frac{ETm_i - ETa_i}{ETm}]$$

Table 4.12. Measured Relative Grain Yield and Calculated Relative Grain Yield using Models Equations

Treatment	Growth Stages Relative ET				Measured Rel. Yield	Cal. Rel. yield			
	I	II	III	IV		J	M	S	BC
3	0.76	0.93	0.99	0.96	0.91	0.93	0.96	0.93	0.93
6	0.97	0.66	0.98	0.98	0.87	0.85	0.86	0.86	0.86
8	0.97	0.96	0.75	0.90	0.78	0.83	0.89	0.82	0.84
13	0.99	0.95	0.90	0.63	0.88	0.82	0.87	0.82	0.83
14	0.73	0.67	0.65	0.68	0.59	0.61	0.63	0.56	0.58

J = Jensen (1968)
M = Minhas et al (1974)
S = Stewart et al (1977)
BC = Bras and Cordova (1981)

4.7 Dry Matter Yield Model

Table 4.13 shows the data used in evaluating Eq. 2.9 for both dry matter and grain yield. The yield reduction factor, that is, the stress sensitivity factor, β_o is tlfe slope of the graph of relative yield decrease versus relative evapotranspiration decrease as shown in Fig. 4.3a for grain and Fig. 4.3b for dry matter yield.

Figure 4.3a shows the relationship between relative grain yield decrease and relative evapotranspiration deficit with a regression equation given as:

$$(1 - \frac{ya}{ym}) = 2.06(1 - \frac{ETa}{ETm}) - 0.0303 \quad \ldots\ldots\ldots\ldots 4.5$$

and a correlation coefficient, r, of 0.9689.

Figure 4.3b is the relative dry matter yield decrease versus relative evapotranspiration deficit with a regression equation given as:

$$(1 - \frac{DMa}{DMm}) = 1.45(1 - \frac{ETa}{ETm}) + 0.0045 \quad \ldots\ldots 4.6$$

and a correlation coefficient, r, of o.9067.

The predictive accuracy of Eqs. 4.5 and 4.6 was tested with the remaining field data as explained in section 3.10. Table 4.14 shows relative evapotranspiration (ETa/ETm) measured,and calculated relative grain and dry matter yields using Eq.4.6 and 4.7

The absolute mean difference between measured relative dry matter yield and calculated relative dry matter yield was 0.016, while the absolute mean difference between relative grain yield and calculative relative grain yield was

Table **4.1 Relative Yields Reduction and Relative Seasonal Evapotranspiration Deficits**

Treatment	1-Ya/Ym	1-Dma/DMm	1-ETa/ETm
1	0.00	0.00	0.00
2	0.07	0.11	0.05
4	0.09	0.13	0.08
5	0.08	0.08	0.05
7	0.23	0.23	0.12
9	0.26	0.18	0.13
10	0.27	0.18	0.14
11	0.08	0.04	0.06
12	0.11	0.12	0.08

Table 4.14 Measured Relative Yields and Calculated Relative Yields using Equations 4.5 and 4.6

		Relative Grain Yield(ya/ym)		Relative Dry Matter Yield(DMa/DMm)	
Treatment	Seasonal Eta/ETm	Measured	Calculated	Measured	Calculated
3	0.94	0.91	0.91	0.91	0.91
6	0.92	0.87	0.87	0.85	0.88
8	0.90	0.78	0.82	0.87	0.86
13	0.90	0.88	0.82	0.89	0.86
14	0.71	0.59	0.43	0.65	0.58

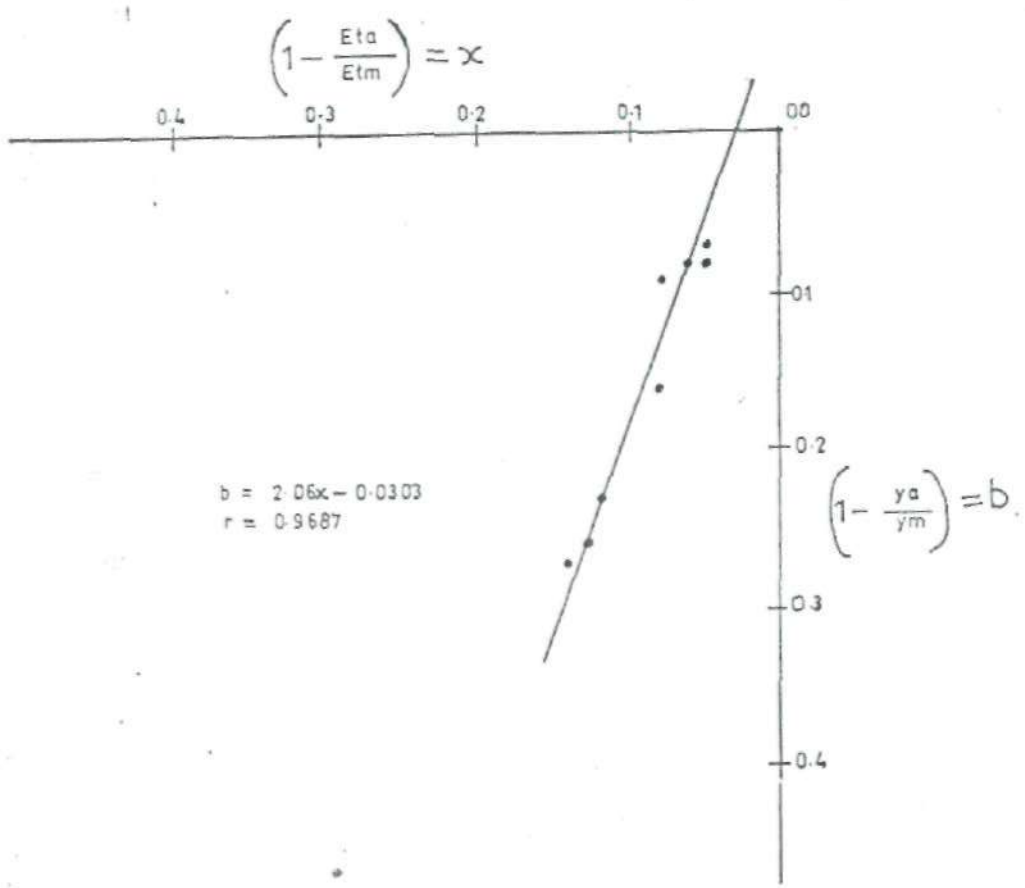


FIG. 4.3a : Relationship btw. Grain Yield Decrease and Relative Evapotranspiration Deficit.

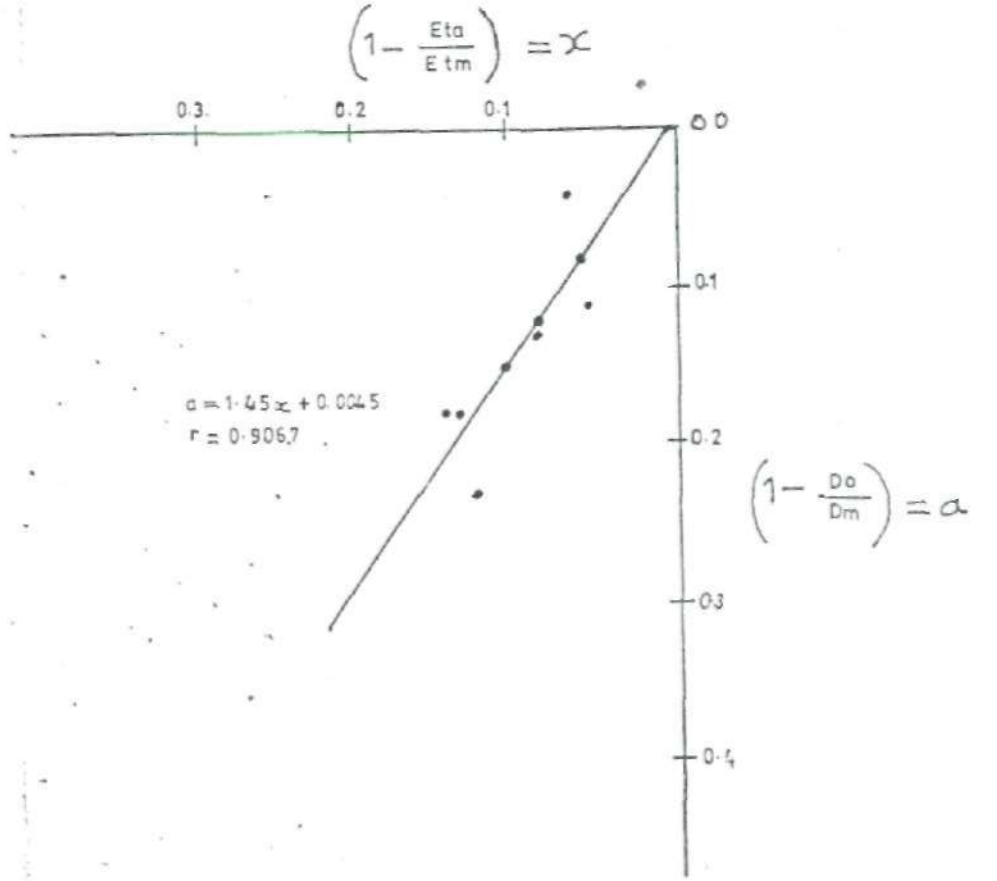


FIG. 4.3b : Relationship btw. Dry Matter Yield Decrease and Relative Evapotranspiration Deficit.

0.036. A statistical analysis showed that there was no significant difference between the measured and calculated relative yields of dry matter, and of grain at 0.05 significant level. This implies that the model adequately predicted dry matter yield and grain yield. However, while the constant coefficient part of Eq.4.6 can be neglected, been approximately Zero the constant coefficient part of Eq.4.5 is necessary for fair prediction of grain yield.

4.8. Water Use Efficiency (WUE) of the Crop

Table 4.15 shows the water use efficiencies for grain yield expressed in kg/ha-mm. The highest value was 6.61 kg/ha-mm for grain yield which was recorded in the control treatment, and the least value (5.43kg/ha-mm) were recorded in the dry treatment. Table 4.16 shows the analysis of varaince for the water use efficiencies. The result shows that the mean difference between the water use effeiciency of the control treatment and the stresses treatment was significant at 0.05 level of significance. The mean difference of the water use efficiency of the dry treatment versus the stressed treatment was highly significant. This result illustrate the importance of attaining relatively high yield for high water use efficiency. It also emphasizes the importance of limiting the duration and severity of moisture stress and attaining relatively high yield when limited irrigation management is practiced. The highest water use efficiency of 6.61kg/ha-mm for grain yield was found to be approximately equal to the 6.6kg/ha-mm of water obtained by Chaudhury and Kumar (1980) for wheat under moisture stress in Kadawa Kano state.

Table 4.15 Water Use Efficiency.

Growth Stage	Treat ment	SET (mm)	GY (kg/ha)	WUE kg/ha-mm
control	1	409.0	2700	6.61
	2	389.0	2500	6.44
I	3	383.0	2460	6.43
	4	375.0	2450	6.54
	5	387.0	2480	6.42
II	6	375.0	2340	6.24
	7	360.0	2070	5.76
III	8	369.0	2110	5.72
	9	355.0	2000	5.64
	10	350.0	1980	5.65
IV	11	384.0	2470	6.44
	12	376.0	2390	6.36
	13	369.0	2370	6.45
Dry treatment	14	291.0	1580	5.43

GY = Grain yield WUE = grain water use efficiency

SET = Seasonal Evapotranspiration

Table 4.16 Analysis of Varaince for Water Use Efficiences

Source	Df	SS	MSS	F	Remark
Replication	2	0.005	0.003	0.01	NS
Stressed Treatment	11	4.32	0.39	2.29	NS
Control Treatment VS Stressed Treatment	1	0.52	0.52	3.06	*
Dry treatment VS Stressed Treatment	1	1.52	1.52	8.94	**
Error	26	4.43	0.17		
	41				

NS = Not significant

* = Significant at 0.05 level

** = Highly significant

5.0 SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary:

A farm land of 800m² was seeded to wheat (Triticum aestivum L. CV. sete ceros) in check basins of size 2.5 x 2.0 m² during the 1995/96 cool, harmattan season, under irrigation at the Institute of Agricultural Research farm. The crop was subjected to three levels of moisture stress by withholding irrigation for 4 days, 7days and 9days in excess of the regular 7days irrigation interval at each of the four growth stages considered, while a control treatment plot was irrigated at 7day interval for the entire growing season of the crop. The moisture stress on the crop caused a reduction in grain and dry matter yields. Crop water use was monitored throughout the growing season of the crop for each treatment, and grain and dry matter yields were recorded at harvest.

Two multiplicative type of crop yield models: Jensen(1968), and Minhas et al (1974); and two additive type of crop yield models: Stewart et al (1977) and Bras-Codova (1981) were evaluated using the experimental data, and their stress sensitivity factors were estimated for the four growth stages considered. Their accuracy and predictability of crop yields, were also tested. Water use efficiencies for grain yield were also determined.

5.2 Conclusions.

The following conclusions are made from the results of this work:

1. Very strong linear relationships between crop yield(both grain and dry matter) and seasonal evapotranspiration was found. An evapotranspiration threshold of 69.3mm was required for dry matter yield initiation, and an evapotranspiration threshold of 145mm was required to initiate grain yield. After these threshold values, grain yield and dry matter yield will rise linearly with evapotranspiration, with an increase of 10.2kg/ha in grain yield and 22.5kg/ha in dry matter yield for every 1mm of crop water use..

2. The four crop yield models evaluated were found to adequately and closely predicted crop yield equally well. However, the Jensen (1968) and Bras-Cordova(1981) model were found to be better than the others, with Minhas et al (1974) being least. The stress sensitivity factors for the four growth stages in all the models show that moisture stress in any of the growth stages had significant effect on crop yield, and stress at the flowering to milk dough development has the greatest yield reduction effect on the crop. The Stewart et al's (1977) model for dry matter yield evaluated was found to predict dry matter yield well and grain yield fairly well.

3. The grain yield losses due to the moisture stress caused by the evapotranspiration deficits were relatively equal to the dry matter yield losses at Booting to heading stage, and at soft dough to hard dough development. The moisture stress at flowering to milk dough development had greater yield

reduction effect on grain yield than dry matter yield, while dry matter yield losses were higher than grain yield losses at stem elongation to booting initiation growth stage.

5.3.Recommendation.

The following recommendations are made out of the findings of this work:

a) the crop yield models evaluated in this work and their stress sensitivity factors estimated adequately predicted crop yields and ar e thus recommended for use in this part of the country.

b) these models can be studied for other cereal like maize, sorghum and rice which are popularly grown in this part of the country too.

c) there may be need to estimate stress sensitivity factors for different definitions of the crop growth stage for comparison with those obtained in this work.

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APPENDIX

Weekly Moisture content measured at the field.
(Percent dry weight basis)

Treatment 1 (control treatment)

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
17-16	14.8	12.6	..	..	..	..	..	..
17-23	15.9	9.0	15.6	14.7	19.2	20.7	19.8	21.3
24-30	15.4	7.4	16.4	14.8	19.2	21.0	18.8	20.1
31-37	15.3	8.0	14.3	11.8	17.3	18.0	15.3	16.2
38-44	14.1	7.5	13.4	10.1	15.9	14.8	17.2	16.4
45-51	15.5	7.5	15.5	10.5	16.0	14.8	16.4	17.5
52-58	15.5	6.0	12.0	9.0	16.2	14.1	14.8	14.9
59-65	15.2	5.0	10.0	6.1	14.3	12.6	15.1	16.4
66-72	16.2	6.1	12.1	5.4	16.0	14.3	15.3	18.2
73-79	14.3	6.8	10.7	6.7	14.0	12.5	16.3	15.8
80-86	14.8	8.2	13.1	10.4	14.9	11.3	13.7	15.2
87-93	15.1	9.8	13.2	11.2	14.3	12.9	13.1	12.0

.. Moisture content not measured.

W -- Moisture content two days after irrigation

D -- Moisture content just before the next irrigation

Treatment 2

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting *	W	D	W	D	W	D	W	D
7-16	14.8	12.6	....	....	....	....	....	....
17-23	14.8	9.6	15.6	15.7	20.5	21.0	21.4	22.7
24-30	13.4	7.0	16.6	14.8	18.5	19.2	21.4	22.7
31-41	14.2	6.0	13.1	7.6	18.0	18.3	20.1	22.1
42-48	15.4	7.3	13.4	8.6	14.6	14.0	15.0	15.8
49-55	14.2	6.2	13.4	9.6	13.9	12.7	15.3	15.7
56-62	16.5	6.0	12.1	9.0	13.9	12.8	14.0	14.6
63-69	16.5	6.0	12.1	7.0	12.7	13.4	14.8	14.9
70-76	16.2	5.5	13.6	8.3	13.1	12.7	15.3	16.9
77-83	15.1	7.7	15.0	8.4	13.1	10.4	13.1	15.2
84-90	14.1	6.8	13.0	10.3	14.2	12.9	13.1	15.7

* *Stress period.*

Treatment 3

Depth (mm):	0 - 150		150 - 300		350 - 450		450-600	
Days after planting	W	D	W	D	W	D	W	D
7-16	15.6	13.4	....	....	....	....	....	....
17-23	16.2	10.8	15.3	13.2	18.2	19.2	18.8	21.3
24-30	13.5	6.0	15.9	14.0	20.1	21.2	18.4	20.1
31-44	12.0	5.2	13.1	6.4	17.5	14.8	21.2	20.2
45-51	14.8	6.2	11.9	8.2	14.8	13.6	15.8	17.5
52-58	16.6	5.0	13.8	9.8	12.4	11.7	15.7	16.8
59-65	16.5	5.5	12.8	9.0	12.4	11.7	14.3	14.7
66-72	17.6	6.0	11.0	6.8	16.3	14.7	16.9	15.7
73-79	15.1	7.7	12.1	8.4	14.0	13.4	16.1	14.3
80-86	15.8	10.3	13.1	10.4	15.1	14.1	14.8	13.3
87-93	14.3	8.2	12.2	10.4	14.3	12.1	15.1	16.3

Treatment 4

Depth (mm).	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	13.2	10.8	—	—	—	—	—	—
17-23	15.9	10.2	15.6	15.7	20.5	21.0	21.4	22.1
24-30	14.0	6.4	14.9	12.0	16.2	18.1	21.1	22.8
31-46	15.3	5.2	12.2	6.9	16.0	14.1	19.2	18.2
47-53	15.2	6.0	12.4	8.4	16.0	14.9	18.1	19.5
54-60	16.1	5.5	12.8	8.2	13.0	12.1	14.0	15.5
61-67	16.1	6.0	12.8	8.9	14.2	13.8	14.1	15.5
68-74	16.8	6.8	13.4	9.9	16.2	14.1	16.5	17.1
75-81	14.1	6.4	10.3	9.2	13.1	10.3	14.2	13.1
82-88	14.1	6.3	13.8	8.2	14.2	12.8	12.2	14.4
89-93	15.3	10.3	12.8	10.8	14.2	14.3	14.1	13.8

Treatment 5

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	12.8	10.6	—	—	—	—	—	—
17-23	14.8	9.6	15.5	15.7	20.8	22.0	21.4	22.7
24-30	15.4	7.2	16.8	14.8	20.1	22.2	21.4	22.1
31-37	15.3	8.0	14.3	11.0	16.2	16.4	16.2	18.1
38-44	13.3	7.5	13.4	11.0	14.0	14.1	18.1	15.1
45-55	15.4	5.0	13.0	6.8	13.5	12.5	17.5	18.8
56-62	15.8	6.0	14.0	7.7	14.8	13.5	13.5	14.2
63-69	14.8	6.2	12.2	7.0	14.0	13.5	14.1	15.5
70-76	14.8	5.5	13.6	10.0	13.6	12.7	13.7	13.9
77-83	15.3	7.3	12.6	10.3	14.0	12.7	14.1	13.3
84-90	14.5	6.8	13.3	9.3	16.1	15.7	12.1	14.2

Treatment 6

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	16.4	14.1	----	----	----	----	----	----
17-23	15.8	10.6	15.4	14.2	20.2	21.0	20.4	22.7
24-30	16.4	8.0	15.0	14.8	18.2	20.1	21.2	23.7
31-37	15.1	8.4	15.8	14.0	15.1	14.3	20.1	22.1
38-44	13.4	6.0	12.4	10.1	16.9	14.8	16.0	17.1
45-58	15.0	4.8	12.2	6.2	15.0	12.4	18.4	17.0
59-65	15.9	5.0	12.4	8.9	14.2	12.1	16.0	18.2
66-72	15.2	5.5	15.1	10.3	16.1	14.8	18.4	20.2
73-79	15.2	8.3	12.6	8.0	14.2	10.8	12.1	14.2
80-86	13.8	6.3	13.3	10.4	15.1	12.1	12.8	14.3
87-93	14.3	7.8	12.2	9.3	14.2	10.2	10.8	13.1

Treatment 7

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	14.8	12.4	----	----	----	----	----	----
17-23	15.8	10.9	15.7	15.5	20.4	21.0	21.4	22.7
24-30	16.4	7.0	14.6	12.8	18.3	20.1	21.4	23.1
31-37	15.1	10.1	13.8	12.0	16.1	15.2	18.1	18.9
38-44	14.1	7.3	13.5	10.1	15.6	13.8	16.4	18.4
45-60	15.1	4.2	11.0	5.2	14.6	10.9	15.8	14.6
61-67	16.4	7.4	12.6	8.4	14.1	12.0	14.1	15.3
68-74	15.2	6.3	12.1	8.9	14.1	12.3	15.2	16.3
75-81	14.1	6.4	10.0	9.2	16.2	13.3	16.2	14.3
82-88	15.1	8.2	13.3	10.8	15.3	12.3	13.2	14.3
89-93	15.1	8.3	12.5	10.0	13.1	15.1	13.2	13.9

Treatment 8

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	14.8	12.6	---	---	---	---	---	---
17-23	14.8	9.0	15.6	14.7	19.2	20.7	18.9	21.3
24-30	13.2	7.5	15.6	13.7	18.4	16.7	18.9	20.3
31-37	13.4	7.5	14.3	11.4	14.2	13.1	15.2	16.4
38-44	15.1	7.5	11.5	10.1	15.6	14.8	18.2	18.4
45-51	15.7	6.0	13.4	10.2	16.4	15.3	15.1	16.2
52-58	16.5	5.5	12.2	9.0	15.6	13.9	13.5	14.9
59-69	15.0	4.0	12.0	6.0	14.1	12.5	14.3	15.9
70-76	16.3	6.3	12.1	8.8	12.9	12.7	13.7	13.1
77-83	15.3	8.3	12.6	10.2	14.8	12.3	12.1	13.2
84-90	16.2	10.3	12.3	10.4	15.4	14.2	14.1	13.9

Treatment 9

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	12.4	10.2	---	---	---	---	---	---
17-23	14.8	9.0	15.5	14.7	19.0	20.7	21.2	22.3
24-30	17.4	10.3	16.4	14.0	19.3	20.9	21.4	23.1
31-37	14.3	8.0	13.8	12.0	16.2	14.1	18.4	20.1
38-44	13.3	6.5	12.5	10.1	15.6	14.8	17.8	18.2
45-51	15.2	6.7	13.7	10.2	16.0	14.1	15.1	16.8
52-58	16.1	7.0	12.2	9.8	14.1	13.1	16.2	14.8
59-72	14.1	4.0	11.4	5.6	16.0	12.4	13.4	13.1
73-79	15.1	6.8	13.3	8.3	14.2	12.9	13.8	14.8
80-86	14.3	8.2	13.3	10.2	14.8	13.2	15.5	16.3
87-93	13.2	6.3	10.3	8.8	15.1	13.2	15.1	16.3

Treatment 10

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	14.3	12.5	---	---	---	---	---	---
17-23	15.9	9.0	15.4	14.7	19.2	20.1	18.8	21.3
24-30	14.0	8.4	14.9	12.1	18.2	20.1	17.8	20.1
31-37	13.4	8.3	14.3	11.4	17.3	16.2	15.2	16.3
38-44	13.3	6.3	12.5	10.1	15.8	14.8	18.1	18.9
45-51	14.8	5.6	12.9	10.4	14.3	13.6	15.7	15.3
52-58	16.5	6.0	12.2	9.8	16.6	14.4	13.5	14.5
59-74	14.5	3.8	12.2	5.2	14.6	10.8	16.8	16.4
75-81	15.5	9.0	12.6	9.2	14.3	12.2	14.3	14.1
82-88	14.3	8.2	12.8	9.8	15.1	14.2	15.3	16.1
89-93	12.3	8.9	13.3	12.3	16.1	15.1	13.1	12.3

Treatment 11

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	15.3	13.1	---	---	---	---	---	---
17-23	15.9	9.0	15.6	14.7	20.0	21.1	21.0	23.3
24-30	16.4	7.4	15.6	13.4	19.0	22.1	21.0	22.2
31-37	14.3	8.0	13.8	12.0	15.2	15.9	18.2	18.4
38-44	14.1	7.5	12.4	10.6	15.1	13.8	20.4	19.3
45-51	15.7	6.9	13.7	10.2	13.6	12.3	16.1	16.3
52-58	16.5	6.0	12.2	9.8	14.3	12.6	14.2	15.2
59-65	15.2	5.0	10.0	5.8	14.2	12.1	15.0	16.8
66-72	16.2	6.0	12.2	9.4	14.1	13.8	15.1	14.2
73-83	15.8	5.8	13.2	8.6	14.1	12.2	15.1	14.9
84-90	14.2	10.3	12.2	10.3	14.1	12.3	14.1	13.1

Treatment 12

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	14.9	12.6	---	---	---	---	---	---
17-23	14.9	8.8	15.6	14.7	19.2	20.7	19.8	21.3
24-30	13.2	7.5	15.4	13.0	18.4	20.2	20.3	19.8
31-37	14.3	8.0	13.8	12.0	14.1	12.4	18.2	20.1
38-44	13.8	8.0	11.5	10.3	15.6	13.8	20.4	19.3
45-51	15.8	6.9	13.7	10.0	15.7	14.1	14.0	15.6
52-58	15.7	6.7	12.2	9.8	16.6	14.3	16.4	15.8
59-65	14.6	5.5	12.3	8.0	14.1	13.0	15.5	14.3
66-72	16.1	7.2	12.4	8.4	16.1	15.2	20.4	19.8
73-86	14.3	5.2	12.1	6.4	14.4	12.3	16.2	14.8
87-93	14.3	8.3	13.1	11.4	13.2	12.0	14.4	14.2

Treatment 13

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	14.4	12.0	—	—	—	—	—	—
17-23	15.9	9.0	15.4	14.7	19.2	20.7	18.8	21.3
24-30	16.4	7.0	16.4	14.8	19.2	21.0	18.8	21.3
31-37	14.3	8.0	13.4	12.3	15.2	16.1	18.7	17.2
38-44	14.3	8.0	12.9	9.6	15.1	13.3	19.8	20.4
45-51	15.7	6.7	13.7	10.7	15.3	14.2	15.9	16.5
52-58	16.5	6.0	12.2	9.8	14.4	12.6	13.5	14.5
59-65	16.1	6.8	12.8	8.8	15.7	13.7	13.7	14.7
66-72	14.2	6.0	11.2	8.9	14.1	13.8	18.2	16.2
73-88	15.8	5.2	13.2	8.0	15.1	12.8	16.3	15.5
89-93	14.1	8.3	12.8	10.0	15.1	13.2	13.2	14.3

Treatment 14

Depth (mm):	0 - 150		150 - 300		300 - 450		450 - 600	
Days after planting	W	D	W	D	W	D	W	D
7-16	14.8	12.6	—	—	—	—	—	—
17-23	16.9	11.2	15.4	12.7	18.2	20.1	18.2	20.1
24-30	13.5	6.0	15.9	13.0	19.2	21.0	19.2	20.2
31-44	12.8	4.2	12.3	7.2	15.3	14.4	20.2	19.5
45-58	14.3	4.6	12.0	6.4	14.1	10.9	16.1	14.0
59-72	14.9	4.2	12.6	6.0	14.0	10.8	16.3	15.1
73-86	16.3	5.3	12.2	7.8	14.3	10.3	14.9	15.8
87-93	14.3	10.3	12.1	10.2	15.3	14.9	13.3	14.8