DEPARTMENT OF AGRICULTURAL ENGINEERING
AHMADU BELLO UNIVERSITY ZARIA

A TIME-BASED STRESS-DAY INDEX CONCEPT FOR IRRIGATION SCHEDULING

BY

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Being a thesis submitted to the Postgraduate School, Ahmadu Bello University, in partial fulfillment of the requirements for the award of M.Sc Degree in Agricultural Engineering.

November, 1993

DECLARATION

I hereby declare that this thesis has been written by myself 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 references.

---------- Date 8/3/94

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CERTIFICATION

This thesis, entitled "A TIME-BASED STRESS-DAY INDEX CONCEPT FOR IRRIGATION SCHEDULING" by Z. D. Bungwon, meets the regulations governing the award of the degree of Master of Science (AGRIC. ENG.) of Ahmadu Bello University, and it is approved for its contribution to scientific/technical knowledge and literary presentation.

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DEDICATION

To

My aged parents;

Kahu and Dutse Bungwon.

It's your worthy contribution to my life

and to the lives of others

that makes you treasured and honoured

by all.

ACKNOWLEDGEMENTS

I wish to express my profound gratitude to my supervisors, Dr. O. J. Mudiare and Mal. A. Ahmed, for the useful guidance they gave me during the course of the project. I also appreciate the special interest and concern they showed by way of encouragement and making available useful materials towards the success of the project.

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Finally, I acknowledge with deep humility, the love and faithfulness of God to me and to all mankind. Indeed, "all his promises are yea" and the amen is said by me. I thank him for helping me through this project.

ABSTRACT

A time-based concept which provides a quantitative means for estimating the plant water stress imposed on a crop during its growing season to provide a criterion for characterising the need for irrigation is presented, based on the stress -Day Index (SDI) concept. Wheat (Triticum aestivum L.) was used as the experimental crop, at the Ahmadu Bello University Farm during the 1991/92 irrigation season.

The Time-based concept was evaluated by comparing; (1) estimates of plant-based plant water deficits corresponding to specified time intervals at different crop growth stages; (2) the values of water used efficiencies from the time-based concept for irrigation scheduling with results obtained from a conventional irrigation scheduling approach; and (3) Estimating the Correlation Coefficient between seasonal crop water stress and grain yield from the time-based concept.

The results indicated that the time-based form of characterising plant water deficit is less effective with regards to the definition of crop susceptibilities to water deficits as a function of the timing of occurance of the deficit. However, using the time-based concept for irrigation scheduling, an increase of 20.5 per cent in water use efficincy was obtained over that of the conventional approach to irrigation scheduling.

A water savings of 639m^3/ha was observed without any appreciable reduction in grain yield. Besides, the correlation coefficient between the seasonal crop water stress and grain yield from the time - based concept was found to be as high as 0.956 , thereby indicating the suitability of the concept.

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CHAPTER ONE

INTRODUCTION

Irrigated agriculture, which is generally accepted as the solution to the food problem of the arid and semi-arid regions of the world, is heavily dependent on a number of variables for its efficient performance. These variables have strong interactions and can be grouped broadly into those relating to crop management and those relating to soil and water management.

Efficient water management in food and fibre production is becoming more and more emphasized especially in the arid and semi-arid regions of the world, where water resources are limiting. Savings in the cost of conveying water to the farmers' field may help to present the need for efficient water management. Efficient water management is also considered important where there is the need to minimise the adverse environmental effects both to plants and man due to high water table problems. One or a combination of these factors often call for the development of operation plans that would ensure the most optimum use of water in irrigated agriculture.

A sound management of irrigation water ensures that the minimum amount of water which will result in optimum yield in both quantity and quality is applied at precise time intervals. Hiler et al. (1974)

identified improved irrigation timing techniques and intensified water application methods as two areas which offer considerable promise for increasing water use efficiency in irrigated agriculture. Unfortunately, irrigation timing in most projects in Nigeria is based on arbitrary fixed time intervals without constraint on the quantity of water applied (Dalhat, 1988). In the Kadawa irrigation project, for example, irrigation interval is fixed at 7 days (Dalhat, 1988). However, in pratice, many farmers irrigate on schedules determined by water supply agencies or on the availability of a stream of water. Too often, no consideration is given to variations in climatic factors, soil type or croping practices. Obviously, such methods of timing are inefficient in most cases, as they waste water and may induce high deep percolation loses, leaching of nutrients below the root zone or salinity problems. This is evident in the increasing incidence of waterlogging problems in irrigation projects in Nigeria as identified by Maurya (1980).

The problems of waterlogging has earlier been observed in small irrigation schemes in Nigeria by Iqbal (1975). Nwa (1982) also reported that the groundwater table at the Kadawa irrigation project has risen to a level detrimental to crop growth. He reported crop failure in some areas, which he attributed to the high water table. It should be

pointed out here that the higher the water table, the greater would be the risk of the development of salinity problems, and also, the smaller the volume of soil availability for exploitation by the crop root system. These problems, as well as others, such as the leaching of nutrients below the root zone and the increased poor soil aeration are often associated with excessive irrigation.

Nwa (1982) reported that the groundwater table has become a problem in the Kadawa Irrigation Project within 7 years of continous irrigation practice. He noted in a study initiated in 1977 that the water table exists between 0 - 60 cm below the ground surface at the peak of the rains and often rises to within 40 cm of the soil surface during the irrigation season, as against the result of a survey in 1966/67 before the project construction which, as reported by Nwa (1982), showed that there was no water table within 1.5m of the ground surface even during the rainy season. Thus, there is need for the development and maintainance of optimal water use efficiency to utilize a proper water balance and avoid problems of excessive irrigation.

In an evaluation of irrigation performance under high water table conditions, Dalhat (1988) recommended a 2 week irrigation interval under check basin irrigation system for wheat in the Kadawa Irrigation Project as a measure towards the prevention of waterlogging, low crop yield and possible crop failure.

However, a number of factors should be considered in determining the right quantity of water and the right time of application. Since crop growth and yield are determined by plant water stress and only indirectly and partially by the soil water status (Kramer, 1969), irrigation timing should be based on plant water stress which incorporates factors such as, soil water deficits, atmospheric demand, rooting density and distribution, and crop suceptibility, rather than on soil water status alone (Hiler and Clark, 1971). There has been a major change in emphasis away from the influence of soil water deficit on plant growth, water use and crop yeild to the general recognition that plant growth is controlled directly by plant water deficits and only indirectly by soil water deficits (Begg and Turner, 1976). Besides, Hiler et al. (1974) have showed that water can be used more efficiently if plant water stress are used as the criteria upon which the need for irrigation is based.

An improved irrigation technique developed by Hiler (1969) which is a potentially useful concept for optimizing irrigation timing is the Stress-Day Index (SDI) concept where a quantitative means of determining the crop water stress imposed on the crop during its growing period is provided, which is then used as a criterion to characterise the need for irrigation. Besides its use to characterise irrigation requirement, Hiler and Clark (1971) reported that the Stress-Day

Index concept is also applicable to the characterization of drainage requirement of crops. However, this work is concerned with the characterisation of water stress in crops and its application for irrigation timing as a means of preventing or solving problems associated with over-irrigation, notably, high water table problems.

Since it has been observed (Dalhat, 1988) that it is difficult to set up drainage schemes, especially at the Kadawa Irrigation Project, as a result of the presence of an impermeable layer at about 1m depth below the soil surface (NEDECO, 1974), which would serve as long-term solution, irrigation techniques that would result in increased water use efficiencies should be an aspect that offers considerable promise for minimizing the increasing problems of high water tables in the irrigation schemes in Nigeria. Work by Hiler and Clark (1971) and Hiler et al. (1974) indicate the potentials for improved water use efficiency and related developments concerning the Stress-Day Index concept. This study is aimed at developing a simple method of applying the Stress-Day Index concept in our irrigation systems bearing in mind our local peculiarities.

1.1 Objectives

The specific objectives of this study are:

1. To compare a time-based Stress-Day Index timing approach treatment with a conventional irrigation timing approach treatment in terms of

the total grain yield per seasonal crop water use;

2. To use a time-based stress indicator to determine stress indices as a function of stress level for three growth stages of wheat;
3. To establish a relationship between seasonal stress-Day Index and crop yield, based on the study, which could be used to predict yield at given stress conditions; and

CHAPTER TWO

REVIEW OF LITERATURE

2.0 Introduction

The design and operation of efficient irrigation systems require a proper understanding of soil-water-plant relationships in order to obtain reliable information on the irrigation water requirement of particular crops which forms the basis of good water management. This subject matter has been discussed in more details by several researchers such as; Slatyer (1967); Kramer (1969); and Teare and Peet (1983), and, to review this subject here again is considered unnecessary. Thus, emphasis is given only to the inter-relationships in the soil-plant-atmosphere system that are applicable to the development and/or understanding of water management concepts, and more particularly the Stress-Day Index (SDI) concept, as is applicable to irrigation timing, in the study reported herein.

2.1 Moisture Stress in Plants

Moisture stress refers to the physiological condition of water in plants which are unfavourable for optimum plant growth and is unrelated to the usual physical definition of stress that is associated with a deforming force. In other words, a plant is said to be under stress when the conditions of water are

unfavourable for its optimal growth. Crafts (1939) stated that the term stress is somewhat ambigous but could be defined as the state a plant enters when the water potential is sufficiently low to inhibit normal plant processes. This state is dependent on the type of plant species, the variety and the growth stage of the plant.

The moisture stress on a plant is usually influenced by both the soil and plant water status, and since even at adequate soil moisture supply, symptoms of stress could still be observed in plants, moisture stress is as a result of the development of plant water deficits and not necessarily soil water deficits (Datiri, 1982). Infact, at any given soil water condition, the plant may show no symptoms of stress if either the atmospheric demand is low or if the internal solute concentration of the tissues is high. The same plant growing in the same soil moisture condition may show stress symptoms and growth retardation if either the atmospheric condition or internal water status is different. Kramer (1959) reported that internal water deficits in plants are controlled by the relative rates of uptake of water by absorption through the roots and water loss by transpiration, and these are controlled by a complex combination of soil, plant and atmospheric factors such as; solar radiation, both soil and atmospheric temperature, wind, plant rooting system, availability of soil moisture, concentration of soil

solution, and soil aeration.

The water stress produced by the presence of salts in the soil seems to be quite different physiologically from that produced by simple soil water deficit or high evaporative demand. Taylor (1968) observed that when stress is produced by excessive soil salt concentration, the cells are frequently thick and heavy and often, the plants do not exhibit any visible symptoms of wilting as is the case with stress induced by water deficit or high evaporative demand which may induce moderate to severe wilting symptoms in the same variety of plants that do not wilt from salt-induced stresses. The most readily discernable symptoms in plant shoots of lack of moisture are wilting, rolling of leaves and sometimes leaf browning or leaf drop.

2.1.1 The Development of Moisture Stress in Plants

As evapotranspiration from plants proceed from day-to-day, the leaf water potential falls and water moves towards the liquid-air interface from source of high water potentials distributed both throughout the plant and in the soil. Consequently, a progressive reduction in the soil water content and the soil water potential results. Since there must be a gradient of decreasing potential through the water pathway, from the soil to the atmosphere, to provide the driving force for water flow, it follows that there is usually a concomitant plant water potential decline as

evapotranspiration progresses, which results in the development of an internal water deficit in the leaf, stem and root tissues (Datiri, 1982). Thus, water deficit occurs as an inevitable consequence of water flow along a pathway in which frictional resistances and gravitational potentials have to be overcome (Javis, 1975) and not necessarily only when the loss of water by transpiration exceeds the supply from the roots as is so often stated (Begg and Turner, 1976). Also, as long as the plant is transpiring, the soil-plant-atmosphere system is dynamic and is never at equilibrium and hence, although the soil water potential sets an upper limit for the plant water potential, the later may be at a considerably lower value than the former because of the resistance to water movement through the soil and plant (Gardner, 1968). The difference in the water potential between the soil and plant depends on the rate of water uptake from the soil and the water conducting properties of soil and plant (Gardner and Nieman, 1964). In any case, excessive transpiration or slow absorption from dry, cold or poorly aerated soils or a combination of these can cause internal water deficits and consequently the development of plant water stress.

2.1.2 Effects of Moisture Stress on Crop Growth and Yield

It is now amply evident that subjecting crops to stress impairs yield. The data cited by Slatyer

(1967), for example, indicate that when plants are subjected to stress, the stomata close and assimilation is thus reduced. Water stress in plants has been reported (Kramer, 1969) to be exerted in essentially three ways in the following order:

(a) Reduction in cell turgor, as this affect cell elongation and possibly carbohydrate and nitrogen metabolism.

(b) Reduction in carbon dioxide intake rate, as this affects photosynthetic rate, and

(c) Increase in leaf temperature, as this affects the physiological processes of the plant.

The influence of moisture stress on grain yield is undoubtedly complex and depends on the duration, intensity, frequency and timing (in relation to crop development) of the stress, genotype and the level of associated environmental factors, such as nitrogen (NIX and Fitzpatrick, 1969).

Through a survival mechanism, plants react to an imposed stress in an optimal way; that is, plants shed tillers, lose leaves, abort flowers, amongst others, to achieve the maximum yield possible given the degree of drought severity that is imposed at a particular growth period (Stegman, 1983). Generally, seed yields of determinate crops are typically least sensitive to mild stress in the vegatative period, and stress sensitivity also diminishes in the later part of the grain filling period. Work by Howel and Hiler (1975) showed that the

timing of the occurence of a water deficit is more critical with regard to yield effects than is the magnitude of the deficit, that is, a small deficit in the boot through bloom period could reduce yield as much or more than a large water deficit in the other periods. Stegman (1983) reported that irrigation studies as throughly summerised by salter and Goode (1967), have widely demonstrated that stress sensitivity is generally greatest in the floral-pollination periods. For example, it has been reported (Sandhu and Horton, 1977; Lehane and Staple, 1962; Aspinal, et al, 1964; Aspinal 1965; Brown and Vanderlip, 1969; Day and Intalap, 1970) that stress at spike initiation causes the greatest reduction in yield.

According to Asana and Saini (1958) and Asana et al. (1958), under adequate soil water, number of ears have the greatest effect on yield while under stress conditions, the number of grain/ear and the grain weight are most important. Stress in the vegetation stage reduces leaf area, plant size and the potential number of heads (tillers), stress at flower formation results in reduced size of reproductive organs or grain number/ear, while stress at later stages results in reduced kernel size (Asana and Saini, 1958; Asana et al; 1958; Fischer and Kohn, 1966; Baier and Robertson, 1967; Campbell 1968). Hsiao (1973) noted that some reduction in leaf area in the early vegetation period

will often minimally affect yield reproductive organs because reduced leaf area can allow greater canopy light penetration to maintain assimilative capacity, and also, assimilates accumulated during the day may exceed requirements for growth in the night because of other growth limiting factors such as temperature and nutrition deficiencies (Stegman et al, 1980). Likewise, a less stress sensitivity in the later grain filling period appears due to the ability of plants to translocate earlier accumulated assimilates from the stems and leaves to the grain (Boyer and McPherson, 1975; Wardlow 1967; and Gardner et al; 1975).

2.2 Water Flow in the Soil-Plant-Atmoshere System

When a plant is transpiring, water moves through the root surface, up through the plant to the evaporation sites in the leaves and then as vapour into the bulk air. The water movement in the liquid phase of the soil-plant system occurs in response to a difference in potential energy of water in different parts of the soil-plant system (Gardner, 1968), normally from areas of high energy to areas of low energy.

The Principal driving force for transpiration is the difference between the vapour pressures at the evaporating surface and the ambient environment, and the resulting transipiration rate is proportional to

the potential energy gradient that develops in the soil-plant system and is inversely proportional to the flow resistances in the water pathway (Stegman et al; 1980). Following the works of Cowan (1965), Newman (1969), and Gardner (1960), the flow of water from the bulk soil mass through the plant to the atmosphere was described as analogous to that of electric current flow as expressed by Ohm's Law. Assuming steady state flow, this is stated in the form (Gardner, 1965);

$$E = \frac{\psi_s - \psi_r}{R_s} = \frac{\psi_r - \psi_l}{R_p} \quad \ldots\ldots\ldots\ldots 2.1$$

Where;

E = rate of flow of water through the system which corresponds to the transpiration.

ψ_l = leaf water potential

ψ_s = soil water potential

ψ_r = water potential at the root surface

Rs,Rp = Resistance to water flow in the soil and plant respectively

Ritchie and Jordan (1972) reported that when the soil water potential is above a threshold, the evaporative demand (Ed) controls the transpiration, whereas, below the threshold, transpiration is controlled by water uptake by the roots. However, it has been observed that the soil water potential at which plants indicate symptoms of stress is related to the evaporative demand (Demead and Shaw, 1962). An increase in the evaporative demand causes the actual

evapotranspiration (ETa) to drop below the potential evapotranspiration (ETp) due to stomatal activity, and plant stress to ensue at higher soil water potential (Unger et al; 1981).

For a plant undergoing water stress, the guard cells which controls the stomatal action, loose tugor which causes the stomata to close, thus, increasing the resistance for water transport from the leaves (Kanemasu and Tanner, 1969). Slatyer (1967) observed that water deficit may not affect stomatal resistance until a critical potential value is reached, and as water potential decreases further, there is a progressive increase in stomatal resistance. The works of Kanemasu and Tanner (1969) and Ehlig and Gardner (1964) also suggest that stomatal closure due to water stress occurs within a narrow range of leaf water potential with no unique magnitude. The water stress effects on stomatal activity are species dependent (Hsiao, 1973; and Begg and Turner, 1976). Also, plant age, stress history or Osmoregulation process, which is a relative increase in cell solute concentration during a gradual development of stress, may influence stomate-closing leaf water potential levels in many plant species (Meyer and Boyer, 1972) as reported by Stegman et al. (1980).

Cowan (1965) and Hiler and Clark (1971) showed that a steady state water supply function from the soil can be defined as:

$$E = \frac{\psi_r - \psi_w}{R_p} \qquad \text{---------- 2.2}$$

In which case is the maximum rate of water supply from the soil through the plant to the leaves in response to the critical level of leaf water potential ( ), determined to a large extent by the soil moisture content and hydraulic characteristics of the soil and plant; and Rp is as previously defined in Eq. 2.1.

The following analysis followed, assuming steady state condition for two possible situations:

(1) For a non-stressed plant, the evaporative demand (Ed) is less or equal to Ew, and the transpiration takes place at the potential rate. From Eq. 2.2, it can be observed then that when

$E = E_d$, then,

$$\psi_l - R_p E_d \geq \psi_w \qquad \text{.....2.3}$$

and from Eq. 2.1

$$\psi_l = \psi_r - R_p E_d \qquad \text{.....2.4}$$

which indicates that the evaporative demand (Ed) controls the transpiration. This occurs when the leaf diffusion resistance is minimal with stomates wide open (Hiler and Clark, 1971).

(2) For a plant undergoing water stress, the

evaporative demand is greater than Ew, and the rate of transpiration is determined by the value of the water supply function, Ew.

Thus, from Eq. 2.2, it can be observed then that when

$$E = E_w, \quad \text{then}$$

$$\psi_r - R_b E_d < \psi_w \qquad \text{---------- 2.5}$$

and, from Eq 2.1,

$$\psi_l = \psi_w \qquad \text{---------- 2.6}$$

In this case, the transpiration is controlled by Ew.

From the analyses above, it is evident that;

For case (1),

$$\frac{E}{Ed} = 1 \qquad \text{---------- 2.7}$$

and for case (2),

$$\frac{E}{Ed} = \frac{Ew}{Ed} < 1 \qquad \text{----------2.8}$$

Therefore, the aforementioned analysis indicate that some function of E/Ed may be a good indicator of the degree of stress imposed on a plant during its growth.

2.3 Measurement of Evapotranspiration

Evaporation from a vegetated land is frequently termed evaportranspiration to signify the combined effect of the soil-plant nature of the evaporating surfaces. Whether it is from a free water surface, wet

soil or as transiration from plants, evaporation of water is an energy-dependent process involving a change of state from liquid to vapour phase. Thus, evapotranspiration is a process that will be limited either by the amount of external energy available to vapourise the liquid soil and plant water at the sites of evaporation or by the ability of the soil and plant to transport water to the soil-atmosphere and plant-atmosphere interface (Gardner et al; 1975)

Evapotranspiration measurement methods can be broadly classified as actual evapotranspiration methods and potential evapotranspiration methods. The potential evapotranspiration (ETp) is usually defined as an atmospheric quantity which assumes that the evapotransipration flux will not exceed the available energy from both radiant and convection sources. Actual evapotranspiration (ETa), unlike the potential evapotranspiration, allows consideration of the atmospheric variables somewhat separate from the plant and soil effects. No attempt is made to discuss the basic principles and methodology of evapotranspiration measurement here since more detailed discussions are readily available in the literature (Tanner, 1967; Tanner, 1968 and Sellers, 1965). Thus, in order to describe the actual and potential evapotranspiration as applied to this study, only the water balance approach and the combination approach often referred to as the Penman method are considered

in this report.

2.3.1 The Water Balance Method

The water balance method is based on the principle of conservation of mass applied to some part of the hydrological cycle. Conservation of mass, formulated as a mass budget equation requires that, in general, for any given control volume, the inflow rate minus the outflow rate is equal to the rate of change of the water stored. Accordingly, the local evapotranspiration from a vegetated land surface for a soil layer can be estimated from the water balance equation given by Brutsaert (1982):

$$ETa = \frac{1}{h_s}\int_0^{h_s} \frac{\delta\theta}{\delta t}\, dz + P - q_d \quad \text{---------- 2.9}$$

Where;

ETa = Evapotranspiration, mm

h_s = Effective root zone depth

θ = Volumetric soil moisture content

T = Time

p = Precipitation and/or irrigation

q_d = Drainage loses

z = Depth from Soil Surface

In Eq 2.9, all the terms are taken as mean values over a sampling period. Equation 2.9 assumes that surface runoff and net lateral flow from the volume of soil are negligible. Mean values of the finite difference form

of SS/St over the sampling period as a function of depth (Z) can be determined from measurements of soil moisture changes in the soil profile, and P from measurements of the depth of rainfall and irrigation.

The various techniques that could be used for the measurement of soil moisture depletion are extensively discussed by Holmes et al (1967). However, the neutron moisture meter usually is the most preferred over the others since water volume fractions are determined directly, larger volumes of soil usually are sampled and the same volume is measured repeatedly (Tanner, 1967).

The water balance method described here is probably most useful in situations where q_d is negligible so that evapotranspiration is the only depletion mechanism of the moisture content of the soil profile. Otherwise, before the equation can be applied in practice, qd must be estimated or measured.

2 The Combination Method

It is generally accepted that the combination method, often referred to as the Penman method, offers the best means of integrating the various agricultural meteorological observations into an estimate of potential evapotranspiration (ETp). In this method, the evaporation from an open water surface is calculated from the combined heat balance and aerodynamic equations, utilizing measurements of air

temperature and humidity, wind run and number of hours of bright sunshine. A major advantage of the Penman method of evapotranspiration estimate, as noted by Duru and Adewuyi (1979), is that it is capable of computing evapotranspiration over relatively short periods such as one day, which makes it more useful for irrigation planning. However it is also true that the Penman method is the most complex of the simulation methods. Basically, the equation for computing the evapotranspiration from a free water surface (Eo) has the form (as reported by Duru and Adewuyi, 1979):

$$E = \frac{(\Delta/\delta)H + E_a}{(\Delta/\delta) + 1} \qquad \text{-------- 2.10}$$

which can also be written as

$$E = \frac{\Delta}{\Delta+\delta}H + \frac{\delta}{\Delta+\delta}E_a \qquad \text{------- 2.10a}$$

Substituting for the aerodynamic and heat transfer terms, Ea and H respectively, Eq 2.10a is written as (Chow, 1964):

$$E = \frac{\Delta}{\Delta+\delta}\left[R_a(1-r)(0.18 + 0.55n/N)\right.$$
$$\left. - \sigma T^4(0.56 - 0.092\sqrt{e_d})(0.1 + 0.9n/N)\right]$$
$$+ \frac{\delta}{\Delta+\delta}\left[0.35(e_a - e_d)(1 + 0.009U)\right] \text{ - - - - - - - - 2.10b}$$

where:

Ra = Radiation at the outer limit of the earth's atmosphere

e_a = Saturation vapour pressure at air temperature

e_d = Actual vapour pressure of the air

U_2 = Wind speed in miles/day at 2m above the evaporating surface

γ = Psychrometric constant

r = Radiation coefficient

δ = Stefan-Boltzman Constant

Ta = Air temperature

Δ = Slope of the curve of vapour pressure at saturation versus air temperature

n = Actual hours of sunshine

N = Possible hours of sunshine

Besides its complexity, there are variations in some of the terms of the Penman's model that suggest empericism. For example, the aerodynamic term has been variously given by Wallem and Perrin (1962), Chow (1964) and Schwab et al. (1966) respectively as:

$$E_a = 0.26 \quad (e_a - e_d) \quad (1 + 0.01U_2) \quad \text{---- 2.11}$$

$$E_a = 0.35 \quad (e_a - e_d) \quad (1 + 0.0098U_2) \quad \text{--- 2.12}$$

$$E_a = 0.35 \quad (e_a - e_d) \quad (0.5 + 0.01U_2) \quad \text{--- 2.13}$$

and the radiation coefficient r, may vary from 0.05 for a water surface to 0.25 for a "Green Standard

Vegetation Surface" (Wallem and Perrin, 1962). Also, a study at Muguga (Ripley, 1963) as reported by Mc Culloch and EAAFRO (1965), indicated that the weighting factors and has marked dependence on altitude also, and not only on temperature as was formerly assumed. Therefore, MuCulloch and EAAFRO (1965) recalculated a series of Penman tables from the formular:

$$E = \frac{\Delta}{\Delta+\gamma}\left[R_a(1-r)(0.29\cos\Phi + 0.52n/N)\right]$$

$$- \frac{\Delta}{\Delta+\gamma}\left[\sigma T_a^4(0.10+0.90n/N)(0.56 - 0.08\sqrt{e})\right]$$

$$+ \frac{\gamma}{\Delta+\gamma}\left[0.26(1+h/(20000))(1+0.01U_2)(e-e)\right] \quad \text{---- 2.14}$$

Where the terminology are as defined before except that é is saturation vapour pressure at dew point, Φ is the latitude and h is the altitude.

It should be pointed out at this point however that the preceeding paragraph does not constitute a criticism of the Penman's method. It is rather intended to highlight the argument that the method, while apparently the best simulator of potential evapotranspiration, is nonetheless difficult to use.

2.4 Water Use Efficiency

The subject of efficiency in irrigation has been identified in two aspects as has been stated by Hillel (1971), namely:

(1) The technical aspect of applying water with

minimal waste, for example, by minimizing loses during conveyance and distribution of water as well as loses from run off and evaporation during irrigation; and

(2) the agronomic aspect of maximizing returns per unit of water used by the crop.

In this study, only the second aspect is considered, which will henceforth be referred to as the water use efficiency (WUE) in the study reported herein.

The water use efficiency as broadly defined by Viets (1962) is the mass ratio of crop yield to water used. Therefore, the efficiency in the use of water for crop production means growing as much crop as possible for the water used. The yield can be characterised by the end product of a crop such as grain, seed and lint, or by the vegetative components or a combination of both, representing the total biological yield (Howel and Hiler, 1975). Moreover, to avoid confusion the water used must be defined as either the water applied or the water transpired by the crop or the water lost by both transpiration and direct evaporation from the soil, generally termed evapotranspiration. Basing water use efficiency on water applied may not give a good comparison as it may include variable loses by runoff and/or deep percolation. Thus, although this is certainly of more practical importance to farmers, it is of less fundamental interest (Hillel, 1971). Generally, on the

field level, water use efficiency has been associated with evapotranspiration (Howel and Hiler, 1975) because, as noted by Hanks and Hill (1980), it is difficult to separate evapotranspiration into transpiration and evaporation. Accordingly, in this study, water use efficiency is defined as (Hillel, 1971):

$$WUE = \frac{Y}{ET} \qquad \text{---------- 2.15}$$

Where:

Y = grain yield

ET = Seasonal evapotranspiration

Viets (1962) pointed out that crops grown on dryland (no irrigation) frequently use water more efficiently than well-watered crops, but at much lower levels of production, thus, maximizing water use efficiency may not be desirable. However, maximizing yields are seldom desirable from an economic point of view since other resources such as fertilizer, disease control, pest control and labour are not utilized efficiently (Howel and Hiler, 1975). Therefore, a major objective of research in this subject area is to attain high water use efficiency while maintaining high productivity. An optimum water use efficiency, that is, maximum yield subject to local constrains of water availability is desirable for water planners in assesing future water requirements in crop production.

Since it is a ratio, water use efficiency can be

increased by either increasing crop yield by better methods of pest and disease control, plant breeding and/or decreasing evapotranspiration. As stated by Datiri (1982), water use efficiency is also a function of the environment. One of the ways that environment influences water use efficiency is by influencing the boundary layer and stomatal resistance to gas exchange and the internal resistance of carbon dioxide assimilation (Turner and Begg, 1978). Thus, water stress increase water use efficiency but at the expense of yield. Plants may curtail transpiration when the supply of soil moisture becomes limiting, but curtailing transpiration often entails restricting growth (Slatyer, 1967; and Kramer, 1969). It must be noted, however, that generalization about growth in relation to water use is dangerous, since water uptake and plant growth are an integration of the combined and fluctuating factors in the system such as degree of vegetation cover and interception of light by foliage, wetness and exposure of soil surface, availability of water at critical stages of growth (Hillel, 1971).

Hillel and Guron (1973) stated that it appears more promising to attempt to increase water use efficiency by increasing crop yield than by decreasing evapotranspiration, since plants growing in the field are subject to an externally imposed evaporation demand. This statement, though valid for well-watered crop regimes, does not fully explore the possible

implications of limited irrigation water in regions of short and/or costly water supplies. Also, the need for preventing or alleviating high water table problems by reduced water application may demand otherwise. Limited irrigation will presumably decrease crop yields, however, this yield decrease may not be directly proportional to the water deficit imposed on the crop (Howel and Hiler, 1975), and often, may differ depending on the growth stage of the crop at which the deficit is imposed given a certain deficit level. It has been shown (Hiler et al; 1974) that water use efficiency can be improved if the crop susceptibilities to water stress at the different growth stages are taken into consideration in determining when irrigation is needed.

Other methods of improving water use efficiency include; the use of antitranspirants, use of wind breaks and carbon dioxide fertilization (Begg and turner, 1976). However, these methods may have little or no pratical significance in crop production on a large scale.

5 Irrigation Timming Approaches

Different desirable objectives often influence the choice of an appropriate irrigation timing appoach to be adopted for a specific area. The most common objectives, as reviewed by Stegman et al. (1980), are: maximizing yield/area, maximizing yield/water use,

maximizing net profit and minimizing energy requirement. Thus, in employing different parameter thresholds as timing criteria, the guiding concepts often considered are yield responses to irrigation timing, maximizing net return and relative efficiencies of water balance methods.

Present conventional irrigation timing approaches have been comprehensively reviewed by several authors (Liancre and Till, 1969; Stegman et al; 1980; Stegman, 1983). Therefore, in this work, consideration is given only to the Stress-Day Index approach.

2.5.1 The Stress-Day Index Concept

It is now a well known fact that most non-forage crop yields are more sensitive to water stress at certain growth stages than at other stages (Hiler et al; 1974). In addition to the importance of timing effects, early studies also highlighted the importance of stress duration and intensity. Thus, there was a recognised need to define more quantitatively the degree of stress and its consequent effects. In order to reduce these to a practical level, Hiler (1969) developed the Stress-Day Index Concept which provides a decision-making procedure for initiating irrigations when a calculated Stress-Day Index approaches defined critical values in specified growth periods and also, provides a means by which the water deficit indicator is weighted according to the crop sensitivities at the different growth stages so that reduced deficits occur

during the critical stages. The Stress-Day Index is defined as the actual crop stress that is responsible for the reduction of the potential yield of the crop (Hiler, 1969). The Stress-Day Index (SDI) is determined from two components; the Stress-Day factor (SD) and the crop susceptebility factor (CS), and is formulated as follows (Hiler, 1969):

$$SDI = \sum_{i=i}^{n} (SD_i \times CS_i) \quad \text{--------} \quad 2.16$$

Where n represents the number of growth periods considered and subscript i is the growth stage in question.

2.5.1.1 The Stress-Day Factor (SD)

The Stress-Day Factor (SD) has been defined by Hiler and Clark (1971) as the measure of the degree and duration of plant water deficit. That is, at any particular time, it answers the question "how dry is the crop?".

Hiler and Clark (1971) and Hiler et al. (1974) have proposed a number of alternative measurements for approximate quantitative characterisation of the Stress-Day factor. These include among others, leaf water potential, soil water potential, leaf diffusion resistance, percent available soil water, leaf-air temperature differential and stem diameter. Also, assuming a uniform daily evapotranspiration rate, a time-based indicator such as the irrigation period was

proposed as a possible characterisation of the Stress-Day factor. As earlier mentioned, the analysis given in section 2.2 indicate that some function of the ratio; actual transpiration (E) to environmetal evaporative demand (Ed) may also be a good indicator of the Stress-Day factor. The analysis of this ratio at defined phenological periods in both long-term wheat and grain sorghum revealed a 'critical' ortogenetic period approximating to the time from ear emergence through anthesis to early grain development, and the calculated ratios for this 'critical' period were more closely correlated with yield than a number of other indices used to characterise the crop water environment (Nix and Fitzpatrick, 1969). Hiler and Clark (1971) proposed that the Stress-Day factor could be characterised by:

$$SD = 1 - \frac{ET_a}{ET_p} \qquad \text{---------- 2.17}$$

Where ET_a and ET_p, the actual and potential evapotranspiration respectively, are integrated values over a specified time period, preferably but not necessarily one day. However, the form of Stress-Day factor proposed as in Eq 2.17 implies that no crop water deficit occurs until partial stomatal closure occurs and transpiration decreases below the evaporative demand. Thus, although it appears to characterise advanced crop water stress well, it may

not be sensitive to early signals of crop water stress since cell elongation ceases long before stomatal action causes reduction in transpiration (Jordan, 1970) as reported by Hiler and Clark (1971). Also, as discussed by Ritchie (1974), the possibility exists that the yield could be decreased before the evapotranspiration rate is affected by water deficit.

Another possible characterisation of the Stress-Day factor proposed by Hiler and Clark (1971) as mentioned earlier is based
on the leaf water potential. The proposed form is:

$$SD = |\psi_l| \qquad \text{---------- 2.18}$$

in which $|\psi_l|$ is the absolute value of the leaf water potential integrated over a given time period, or an early morning value or some combination of an early morning and mid-afternoon values. Theoritically, a direct measurement of plant water deficit such as the leaf water potential should provide a better indicator than the other plant - based, soil-based and time-based measurements which are indirect indicators of plant water dificit because, as it is now generally accepted, crop growth and yield are determined directly by plant water deficit and only indirectly and partially by soil water status (Kramer, 1969). However, its use may be limited to only highly intensified irrigation installations. For example if the environmental

evaporative demand is high and exceed the maximum water supply rate from the soil, the plant would indicate a water deficit even with a well-watered soil condition in which case, the only appropriate irrigation approach would be misting aimed at reducing the environmental evaporative demand rather than adding water to the soil. Work by Lewis (1973) as reported by Hiler et al. (1974) indicated a better characterisation of the Stress-Day factor by the soil water potential than leaf water potential. This result might be expected because instanteneous values were utilized, and leaf water potential values are much more sensitive to minute-to-minute changes in the evaporative demand than are soil water potentials (Hiler et al; 1974). Therefore, the desired indicator in given circumstances will depend on a number of practical considerations made alongside the theoritical reasoning.

Another possible method of characterising the Stress-Day factor is simply to consider the environmental evaporative demand minus the supply (Hiler and Clark, 1971). Therefore, from Eq 2.1, the formulation would be as follows:

$$SD = E_d - E, \text{ or}$$

$$SD = E_d - \frac{\psi_s - \psi_l}{R_s + R_p} \qquad \text{------- 2.19}$$

in which the terms are as defined previously. Precise determination of the second term on the right-hand side of Eq 2.19 is difficult to obtain and needs highly technical equipments and skill, thus, its application is limited.

Also, since the Stress-Day factor is a function of atmospheric evaporative demand and soil water potential in the root zone among other things, an emperical approximation of the Stress-Day factor (SD) could be in the form (Hiler and Clark, 1971):

$$SD = E_d \times / \Psi s / \quad \text{---------- 2.20}$$

Where $|\Psi s|$ is the absolute value of the integrated soil potential in the root zone measured in early morning and Ed is the daily evaporative demand.

2.5.1.2 The Crop Susceptibility Factor (CS)

The Crop Susceptibility factor (CS) depends on the species and the stage of development of the given crop at time of occurence of water deficit, and indicates the crops sensitivity to a given water deficit (Hiler and Clark, 1971). Thus, it answers the question, "How much will crop yield be reduced by a given plant water deficit occuring at a given growth stage?. Hiler and Clark (1971) and Hiler et al. (1974) determined experimentally crop susceptibility factors as the fractional reduction in yield resulting from a fixed, predetermined critical water deficit during a

given growth stage. That is;

$$CS_i = \frac{X - X_i}{X} \qquad \text{---------- 2.21}$$

Where;

X = Marketable yield from a non-stressed treatment

X_i = Marketable yield from a treatment that was subjected to a water deficit at the i^{th} growth stage.

Another method proposed by Hiler and Clark (1971) for characterising the crop susceptibility factor is to plot the crop yield versus cummulative Stress-Days for a given growth period. The value of the crop susceptibility for each period is determined as the slope of the plot related to that growth period. That is,

$$CS_i = \frac{SD_i}{\Delta Y} \qquad \text{---------- 2.22}$$

where i donotes the growth stages. By this method, it should be noted that the crop susceptibility factor is not determined independently of the stress-Day factor. Also, while the stress-Day factor is only an incremental value, the yield is a total value for the growing season (Hiller & Cleark 1971). Data are available for approximate crop susceptibility factor estimates (Day and Intalap, 1970; Datiri and Maurya, 1982), although the different data sources may indicate

differing magnitudes of crop susceptibility factors for the same growth stage of a given crop. Stegman et al. (1980) attributed these discrepances to differing definitions of growth stage length, differing methods of stress-Day characterisation and differing levels of stress-Days at which the crop susceptibilities were defined. The incomplete definition of the crop susceptibilities as complete functions of stress indicators have hampered the implementation of the stress-Day index concept (Stegman, 1983). This implies that to precisely utilize the stress-Day Index concept, experiments are needed to determine crop susceptibilities not only as functions of crop species and growth stages, but also as functions of the level of water deficits.

CHAPTER THREE

MATERIALS AND FIELD MEASUREMENTS

3.0 Introduction

The experiment was conducted at the Ahmadu Bello University Farm, Samaru- Zaria (Latitude 11° 11'N, longitude 07° 38'E) using check basin irrigation system during the 1991/92 cool, dry harmattan season. Wheat (Triticum aestivum L.) was used as the experimental crop.

The climate of the experimental area can be divided into three broad seasons, namely;

(i) The cool dry harmattan season, from October to February,

(ii) The hot, dry season, from March to May; and

(iii) The warm, rainy season, from June to September.

3.1 Physical Characteristics of the Soil

For the purpose of textural classification of the root zone soil profile of the experimental site, a mechanical analysis was conducted on soil samples taken at 150mm depth increments down to a depth of 600mm below the soil surface. The mechanical analysis was a combination of sieve and sedimentation techniques using the standard procedure reported by loveday (1974). Also, in order to determine the soil water holding characteristics of the root zone profile, the moisture content at field capacity and at wilting point

conditions were determined at $0.3x10^5$ and $15x10^5$ N/m^2 respectively for the 150mm soil depth increments up to 600 mm below the soil surface using the generated soil moisture characteristic curves ($\theta = \theta(\ s)$) explained in section 3.2. The $0.3x10^5$ N/m^2 soil suction value was used for the field capacity in view of the light nature of the soil. Table 3.1 shows both the soil textural classification and the soil moisture holding characteristics for the experimental site.

Table 3.1: Soil Textural Classification and Moisture Holding Characteristics

Soil layer (mm)	Soil* Texture	Bulk density g/cm^3	Field Capacity cm^3/cm^3	Wilting Point cm^3/cm^3	Available Moisture (mm)
0 - 15	Loam	1.55	0.2308	0.1285	15.4
15-30	Clay Loam	1.44	0.2227	0.1247	13.2
30-45	Clay Loam	1.43	0.2478	0.1554	13.9
45-60	Clay Loam	1.27	0.2538	0.1503	15.5
Total					58.0
Average	-	1.47	0.2588	0.1422	-

* USDA Classification

3.2 Soil Moisture Characteristic Curves

Soil moisture characteristic curves for 150mm soil depth layers upto the 600-mm root zone depth where developed. The following steps were taken to develop the curves:

(i) The soil moisture contents at 5 different soil suctions were determined for 150-mm soil depth increments up to 600 mm below the soil surface

using the pressure plate apparatus in the laboratory.

(ii) For each of the 150-mm incremental depths, the points P_i (h_i, θ_i) were located on a logarithmic paper, and the line of best fit drawn to represent the soil moisture characteristic curve for each soil layer.

Also, the average soil moisture characteristic curve for the entire 600-mm root zone depth was developed following the procedure outlined above, using average soil moisture content and the corresponding soil suction values for the entire root zone depth. The developed soil moisture characteristic curves are shown in figures 3.1A-E.

3.3 Experimental Treatments

The treatments used for the study are related to the three growth stages of wheat given in Table 3.2

Table 3.2: Growth stages of Wheat used in the study.

Growth Stage	Description	Period (days after seeding)
I	Stem elogation - Booting	31 - 55
II	Ear emergence - Flowering	56 - 69
III	Milk-Dough development	70 - 83

Refering to the principal growth stages for cereals as described by Zadoks et al. (1974), growth

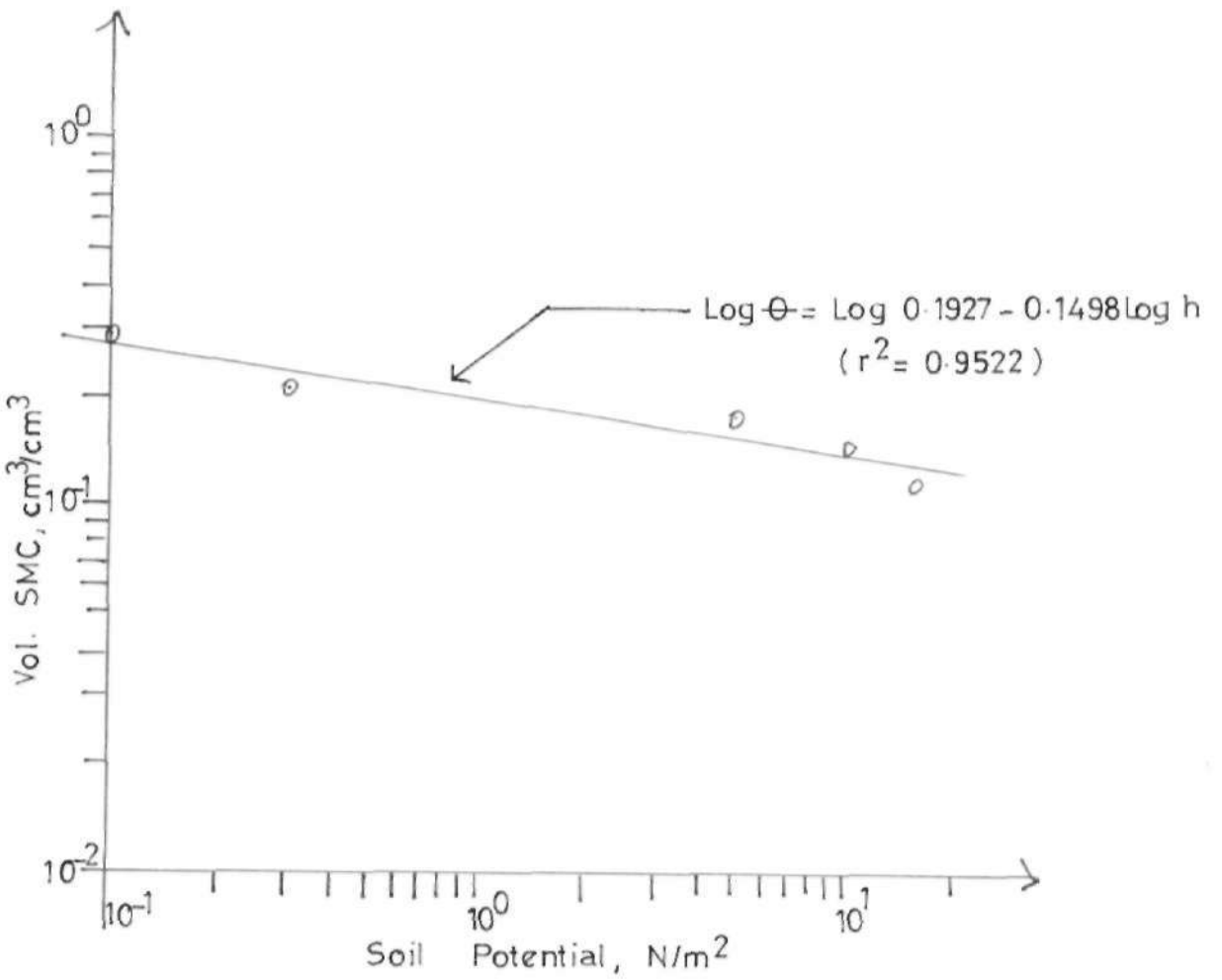


Fig. 3·1A : Characteristic Curve For Soil Layer 0 - 150 mm

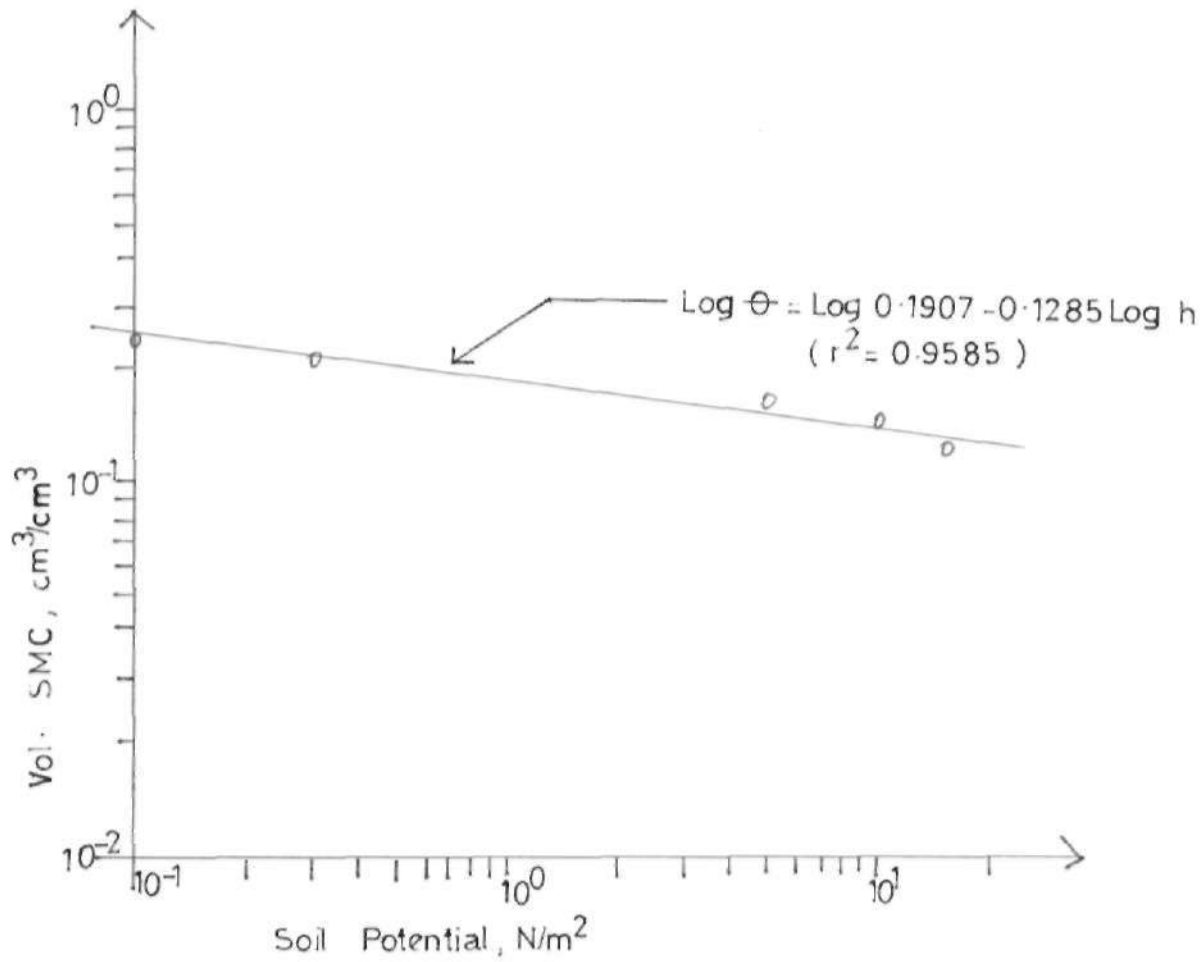


Fig. 3.1B: Characteristic Curve For Soil Layer 150 - 300m m

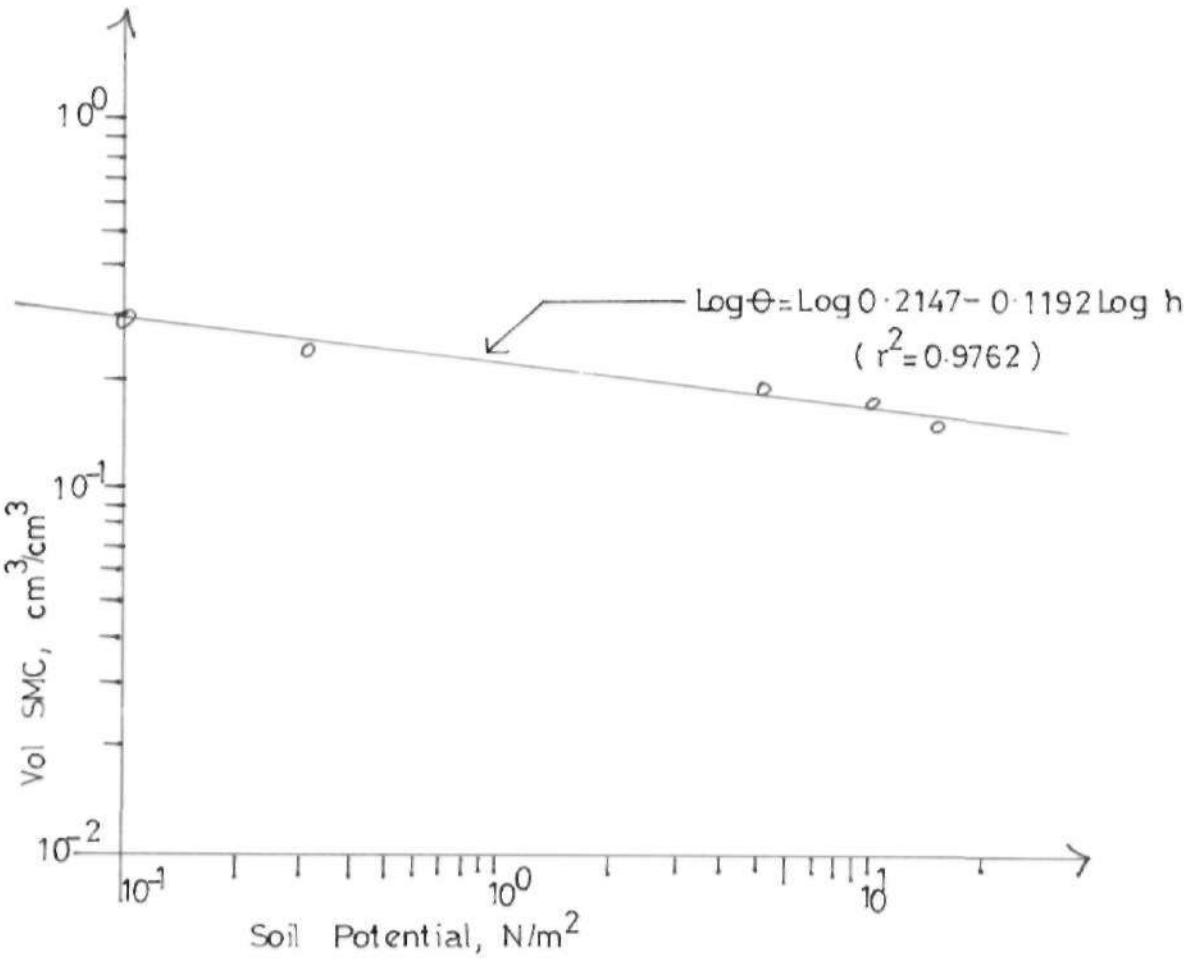


Fig. 3·1C : Characteristic Curve For Soil Layer 300-450mm

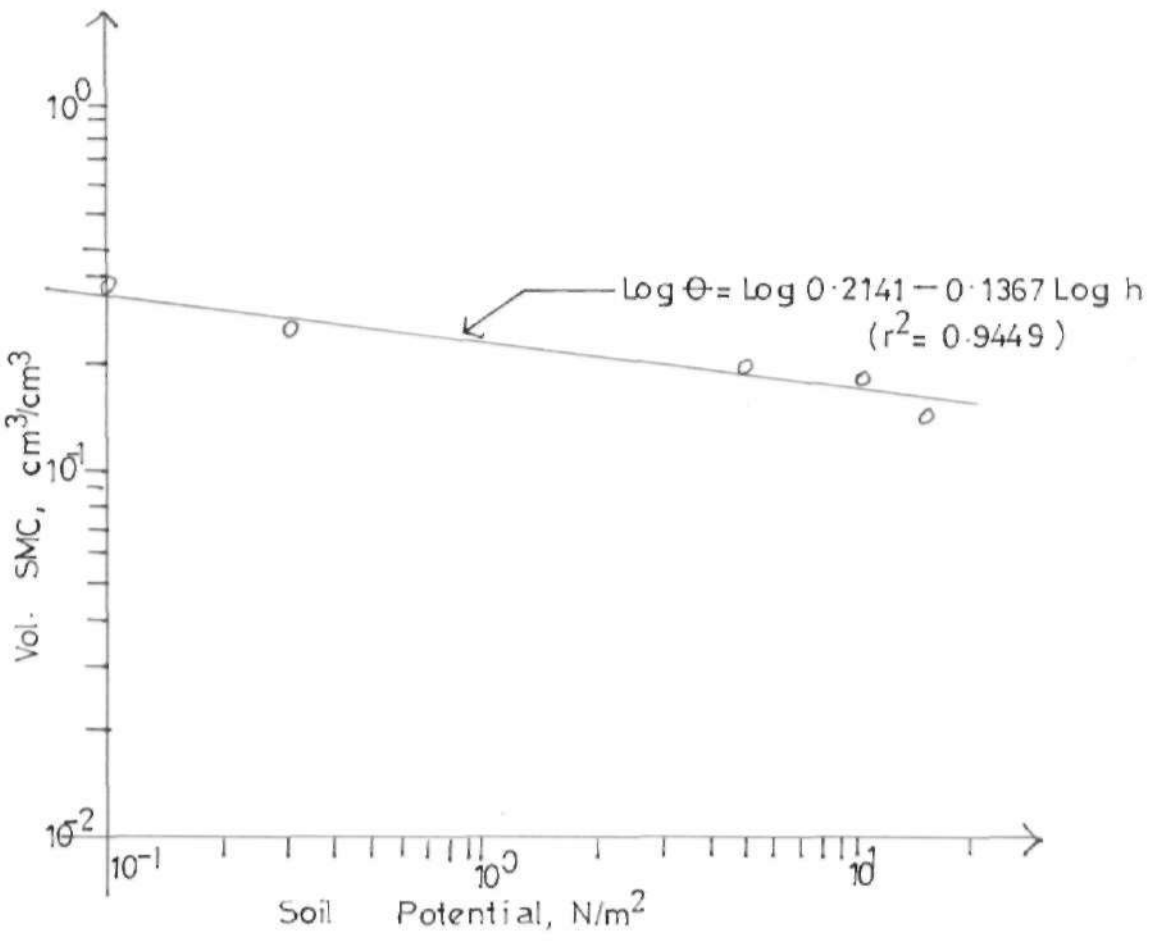


Fig. 3·1D: Characteristic Curve For Soil Layer 450-600mm

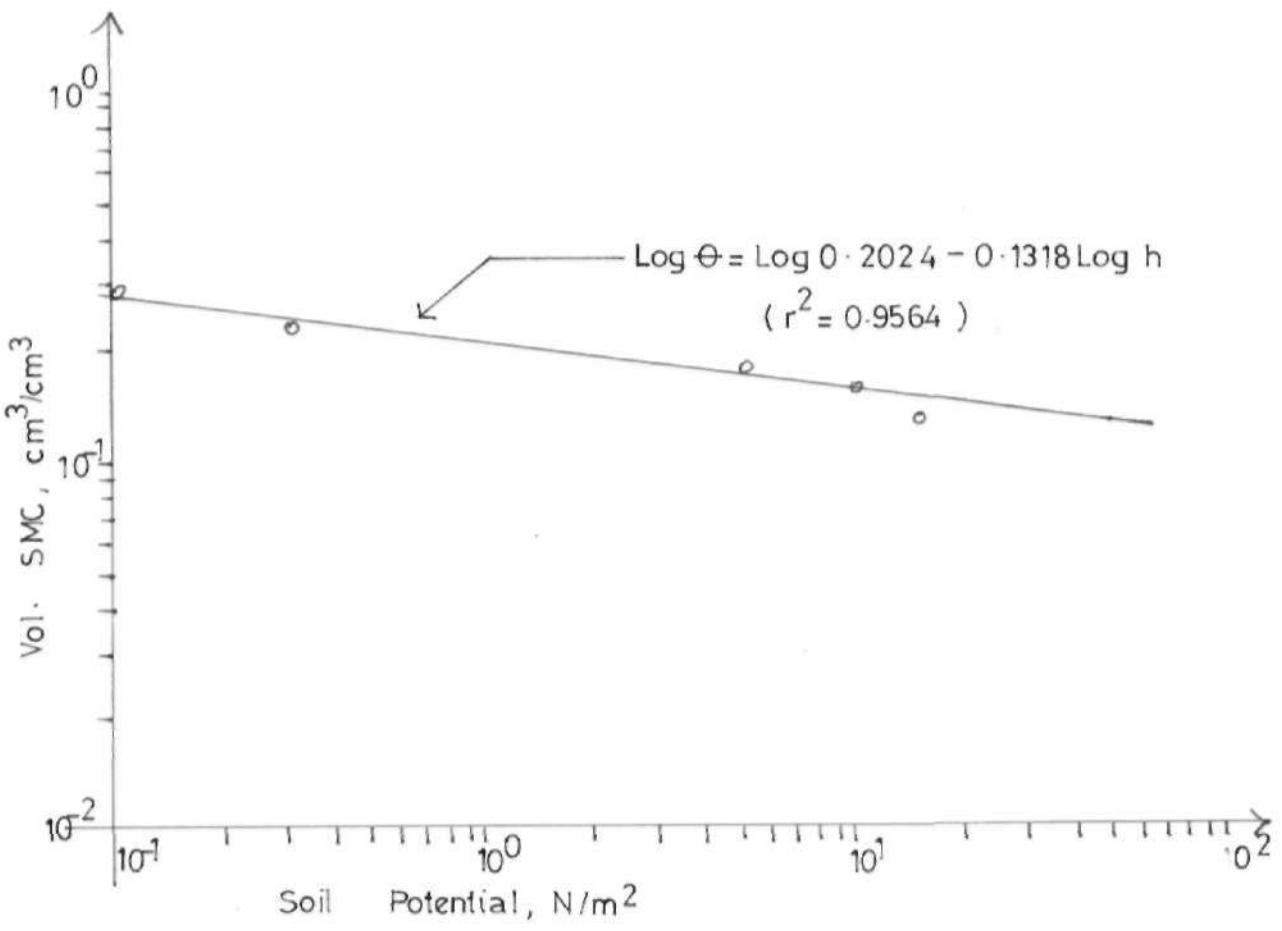


Fig. 3·1E: Characteristic Curve For The Entire 0-600-mm Depth

stage I include stages three and four; stage II include stages five and six ; and stage III include stages seven and eight. The growth stages of cereals as described by Zadoks et al (1974) are given in Appendix A.

Following the local "standard practice" of a 7 - day irrigation interval for wheat, the control treatment was irrigated using a 7 day irrigation interval throughout the growing season until irrigation was cut off completely on the 28th February 1992. The Stress-Day Index (SDI) treatment amounted to varying the number of days between irrigations for each of the growth stages considered. A detailed working procedure for the determination of the number of days between irrigations for this treatment at the three growth stages is given in section 3.3.1. Further, twelve other treatments were obtained by imposing four levels of moisture stress at the three growth stages considered. These are henceforth referred to as stressed treatments herein. The four levels of stress, namely, a,b,c, and d for the stress treatments were choosen as 3,7, 10 and 14 days respectively above the control's 7-day irrigation interval. The experimental treatments used for this study are given in Table 3.3.

3.3.1 The Stress Day Index (SDI) Treatment

Irrigation scheduling is accomplished with the Stress-Day Index concept by irrigating when the daily Stress-Day Index reaches some pre-determined critical

Table 3.3: Experimental Treatments

Treatment	Description
C	Regular 7-day irrigation interval throughout the growing season.
SDI	Variable irrigation intervals depending on crop growth stage.
AI	Stressed once to level 'a' at growth stage I, no stress during other growth stages.
BI	Stressed once to level 'b' at growth stage I, no stress during other growth stages.
CI	Stressed once to level 'c' at growth stage I, no stress during other growth stages
DI	Stressed once to level 'd'at growth stage I, no stress during other growth stages.
AII	Stressed once to level 'a' at growth stage II, no stress during other growth stages
BII	Stressed once to level 'b' at growth stage II, no stress during other growth stages
CII	Stressed once to level 'c' at growth stage II, no stress during other growth stages
DII	Stressed once to level 'd' at growth stage II, no stress during other growth stages
AIII	Stressed once to level 'a' at growth stage III, no stress during other growth stages.
BIII	Stressed once to level 'b' at growth stage III,no stress during other growth stages.
CIII	Stressed once to level 'c' at growth stage III, no stress during other growth stages.
DIII	Stressed once to level 'd' at growth stage III, no stress during other growth stages.

value, SDIc (Hiler et al, 1974). Theoritically, the value of SDIc should depend on the availability and/or cost of water. It may also depend on the prevailing drainage requirements of the area. However, as it is often the practice, SDIc was set equal to the seasonal average Stress-Day Index which would result from the schedule of irrigation in each growth stage at Stress-Day (SD) levels typical of the "Standard Practice" (Stegman et al; 1980). Thus, adopting the 7-day irrigation interval criterion as the "Standard Practice" in the study area for wheat, the value of SDIc was calculated and the corresponding Stress-Days in terms of the number of days between irrigations at each of the growth stages considered were determined as given in Table 3.4.

From Table 3.4, the stress-Day index treatment amounted to 10, 7 and 5 day irrigation intervals during growth stages I, II and III respectively.

3.4 Field Layout and Experimental Design

The experiment consisted of fourteen treatments replicated three times. The details of the treatments are given in Table 3.3. Using a completely randomised block design, three blocks were laid along the general slope of the field in order to ensure as much homogenous soil condition as possible within a block. Each block consisted of fourteen basins corresponding to the number of treatments, in two rows of seven basins each, each basin measuring 2.5m x 2.5m.

Table 3.4 Determination of Irrigation Intervals for the Stress Day Index Treatment

Growth Stage	*CS	SD (days)	+SDI (days)	ISDI$_c$ (days)	$SD$$_i$ (days)
I	0.1034	7	0.7238	0.9772	10
II	0.1329	7	0.9303	-	7
III	0.1825	7	1.2775	-	5
			2.9316		

* Source: Datiri and Maurya (1982)

\+ SDI = CS X SD

I SDI_c = Average SDI = 2.9316/3 = 0.9772

$ $SD_i = SDI_c/CS$

On difference soil types, Doneen (1971) observed a miximum lateral water movement of about 75cm from the centre of a furrow. Therefore, in order to avoid possible errors due to the seepage of water from one basin to another as a result of lateral flow of water, each basin was separated from the adjacent basins by 1-m wide land strips on all sides. Figures 3.2 and 3.3 shows the contour map and the detailed layout design of the experimental field respectively.

3.5 Field Operations

The field was seeded with wheat (Triticum aestivum L) at a seed rate of 100 kg/ha in already prepared besins on the 4th December, 1991. Thereafter, the basins were flooded with water to raise the root zone

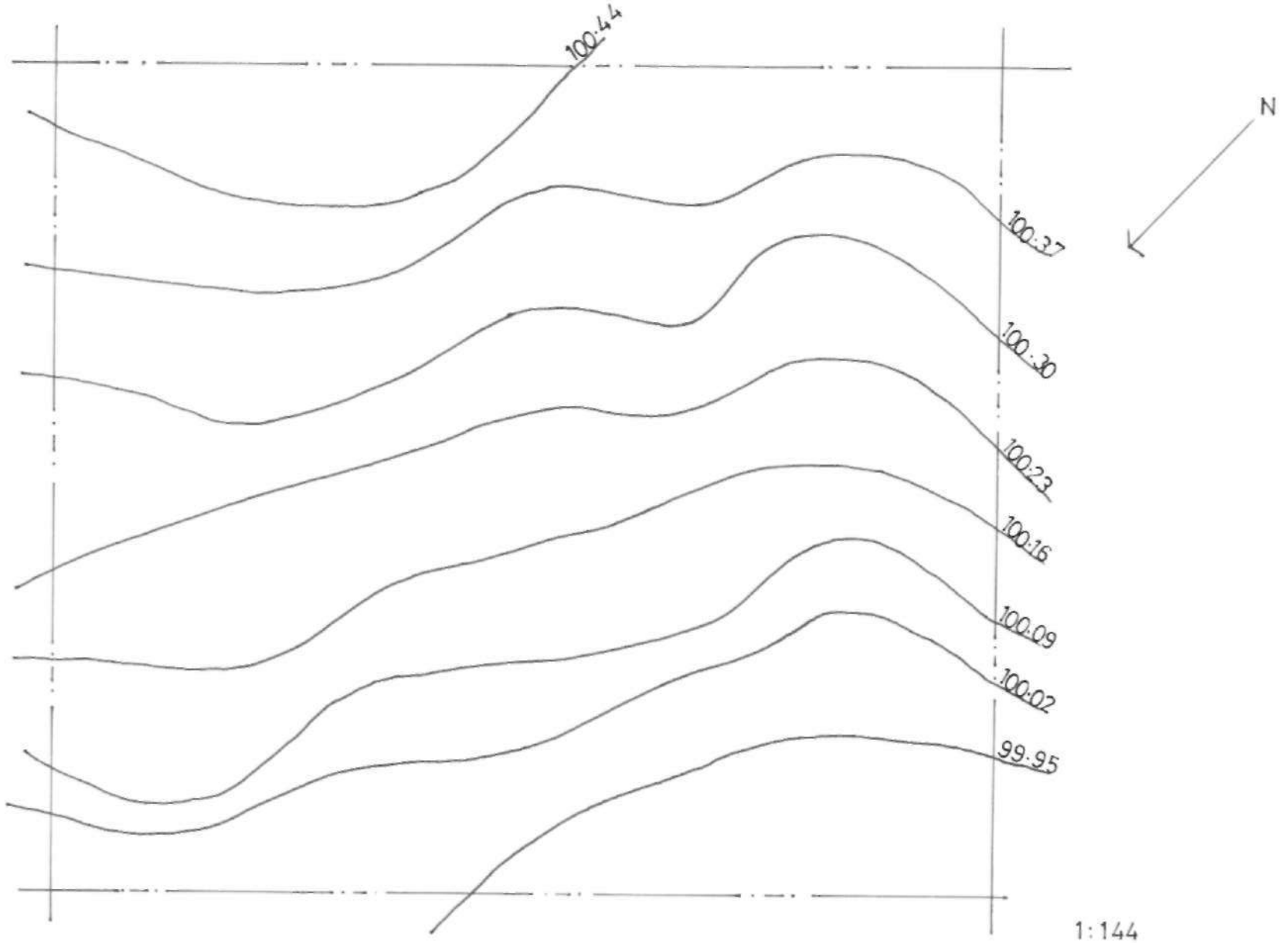


Fig. 3·2: Contour Map of The Experimental Field



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Fig. 3.3: Layout Design of Experimental Field

(taken as the top 600-mm soil layer) to field capacity. Irrigation was done at 7-day intervals up to the 31st December, 1991 after which the various treatments were imposed. Compound fertilizer was applied as basal dosage at a rate 60kgN_2/ha, 60kg P_2O_5/ha and 60kgK_2O/ha just before seeding. Later, this was followed by a top dressing with CAN at a rate of 60kgN_2/ha 5 weeks after seeding. The need for weeding did not arise throughout the growing season as the plots were free from weeds. Accordingly, no weeding was done on the experimental field throughout the growing season.

3.6 Irrigation Practice

Irrigation was done at frequencies obtained by the treatment design during the growing season until 28th February, 1992 (84 days after seeding) when irrigation was cut off from all the treatments after observing that the crop was fully ripe. Irrigation was done by applying the amount of water needed to raise the root zone to field capacity at each irrgation. Thus, the irrigation amounts were determined as the actual evapotranspiration for the irrigation intervals, which were determined by the water balance approach as explained in section 3.8

A potable petrol water pump was used to lift water from a pond and applied to the respective basins using coupled pipes. The pump discharge, Q was computed on each irrigation from the average time, T it takes to

fill a container of known volume, V placed at various positions on the experimental field. That is;

$$Q = \frac{V}{T} \qquad \text{.....} \quad 3.1$$

Where;

Q = Pump discharge (l/sec)

V = Volume of container (l)

T = Time to collect the given volume, V (Sec)

Due to small basin sizes, it was observed that the spread time was negligibly small when compared with the application time, T_a. Therefore, from Eq. 3.1, the application time for basin i on day j, Ta_{ij} was determined as:

$$Ta_{ij} = \frac{V_{ij}}{Q_j} = \frac{I_{ij} \times A}{Q_j} \qquad \text{.....} \quad 3.2$$

Where;

V_{ij} = Irrigation amount for basin i on day j, (l)

I_{ij} = Irrigation amount for basin i on day j, (mm)

A = Area of basin = 6.25 m2

Q_j = Pump discharge on day j, (l/Sec)

3.7 Soil Moisture Content Measurements

The soil moisture content measurements were conducted using the grammetric method. Soil samples for the soil moisture content determination were taken, using a soil auger, a day before each irrigation and 2 days after irrigations at incremental depths of 150mm

down to a depth of 600mm below the soil surface. The samples were weighed using an electronic balance (Mettler P10) before and after drying, which was done in an electric oven (Shermond 2000) at 105°C for about 24 hours to ensure that all moisture is driven off. However, samples were not taken from the other treatments prior to their respective stress periods since it was expected that the results obtained from the control treatment plots would also be applicable to the plots where water stress has not been imposed. Again, soil sampling for soil moisture content determination 2 days after irrigation was discontinued after the fourth sampling since it was observed that the soil moisture content values were consistently close to the field capacity values obtained from the pressure plate apparatus analysis (See Table 3.5).

Table 3.5: Soil Moisture Contents Measured Two Days After Irrigation Versus Soil Moisture Content Values at Field Capacity.

Sampling Depth (mm)	Measured Moisture Contents (cm^3/cm^3)				Field Capacity cm^3/cm^3
	30	37	45	52	
	(days after seeding)				
0 -15	0.2101	0.2142	0.2260	0.2187	0.2308
15-30	0.2560	0.2648	0.2491	0.2436	0.2227
30-45	0.2870	0.2816	0.2593	0.2621	0.2478
45-60	0.2582	0.2576	0.2590	0.2590	0.2538

The moisture content measurements data are shown in Appendix B.

In order to convert the gravimetric soil moisture content to volumetric moisture content, the average bulk density of each of the 150-mm soil layers given in

Table 3.1 were employed. The volumetic moisture content, θ as calculated as:

$$\theta = m\rho \quad \text{..... 3.3}$$

Where;

ρ = dry bulk density, (g/cm^3)

m = gravimetric soil moisture content, (g/g)

The depth of water, SWi contained in any soil layer, i of depth Z_i was computed as:

$$Sw_i = \theta_i Z_i \quad \text{..... 3.4}$$

in which θ_i is the measured volumetric soil moisture content of the soil layer. Thus, the volumetric soil moisture content for the entire root zone profile was obtained as:

$$\theta_p = \frac{\Sigma\theta_i Z_i)}{Z}$$

$Z = \Sigma Z_i$ = Total root zone profile depth, which was taken as 600 mm.

3.8 Determination of Actual Crop Evapotranspiration

The actual crop evapotranspiration was determined by the water balance method using soil moisture content

measurements in conjunction with the soil moisture holding characteristics of the soil, given in Table 3.1.

By the adoption of the check basin irrigation system, run-off was eliminated, and groundwater contribution was considered nill as there was no indication of the ground water table within 1.5 m below the soil surface in the experimental site. Thus, the actual crop evapotranspiration was determined based on Eq 2.9. Since irrigation amounts were based on the estimated amounts needed to raise the root zone to field capacity at each irrigation, the drainage component was considered negligible. Also, since soil moisture content measurements taken two days after irrigation for three consecutive irrigations agree reasonably well with the field capacity soil moisture content for the root zone profile obtained from the laboratory, it was considered safe to assume that the root zone was raised to the field capacity at every irrigation throughout the irrigation period. Thus, the actual crop evapotranspirations between irrigations were determined on the basis of the change in soil water storage, which gives the mean values of the finite difference form of $\delta\theta/\delta t$, at 150 - mm soil depth increments for the 600-mm root zone profile from the day of each irrigation, when the soil is raised to field capacity, to a day before the next irrigation, since soil samples were taken a day before each

irrigation.

That is, the actual crop evapotranspiration in mm/day was obtained as:

$$ET_a = \frac{\Sigma\ (SW_{fi} - SW_{mi})}{N} \quad \ldots\ldots\ldots \quad 3.6$$

Since,

$$SW_i = \theta_i Z_i, \quad \ldots\ldots\ldots\ldots\ldots \quad 3.4$$

$$ET_a = \frac{\Sigma\ (\theta_{fi} - \theta_{mi})\ Z_i}{N} \quad \ldots\ldots \quad 3.6a$$

Where;

SW_{fi} = Field capacity soil water in layer i, (mm)

SW_{mi} = Measured soil water in layer i on the sampling day, (mm)

θ_{fi} = Soil moisture content at field capacity for layer i, cm_3/cm_3

θ_{mi} = Measured soil moisture content in layer i on the sampling day, cm_3/cm_3

N = Number of days since last irrigation to the day of sampling

The actual crop evapotranspiration was also estimated using the potential evapotranspiration, obtained from meteorological data (See section 3.9), and crop factors. The actual evapotranspiration, ET_a was calculated as:

$$ET_a = ET_p \times K_c \quad \ldots\ldots\ldots\ldots\ldots \quad 3.7$$

Where;

E_p = Potential evapotranspiration, mm

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K_c = The crop coefficient factor

Crop coefficient factors obtained by Abdulmnimin (1989) for wheat expressed as a function of percent growth of the crop were used in this study.

3.9 Determination of Potential Evapotranspiration

Meteorological data obtained from the Institute for Agricultural Research Meteorological Station in Samaru were used to estimate the potential evapotranspiration. These meteorological data which were recorded at the station on a daily basis were averaged over a period chosen to correspond to the irrigation interval of the control treatment. The averaged values, given in Table 3.6 were used to obtain the values of the terms in Eq. 2.14 by using the relevant table from the tables prepared by Mc Culloch and EAAFRO (1965) for the rapid computation of the Penman evaporation estimate (See Appendix c). Since no table is supplied for the evaluation of the wind component, J, it was determined from the equation (Mc Culloch and EAAFRO, 1965):

$$J = 1 + 0.0IU \quad \text{---------- 3.8}$$

Also, because the recorded dew point temperature means were lower than those obtainable on the tables, a regression analysis was carried out to obtain expressions of regression lines at various mean air

Table 3.6 Meterological Data Averaged over 7 - Day Periods

Period (days from- Seeding)	Mean Temperature (°c)	Wind Run (Miles/Day	Dew Point Temperature (°c)	Hours of Sunshine (Hours)
1 - 7	22.64	47.63	-1.00	9.39
8 -14	20.57	108.73	-2.00	5.36
15-21	19.29	78.89	-3.14	7.89
22-28	19.50	110.40	-1.57	8.14
29-35	15-79	136.54	4.43	1.24
36-42	17.71	124.47	4.07	5.26
43.49	20.79	77.21	3.79	7.31
50.56	22.43	68.18	3.71	5.76
57-63	23.21	72.99	-4.71	9.23
64-70	22.14	131.08	-4.57	7.76
71-77	22.14	127.26	-12.07	7.94
78-84	23.79	112.58	-9.00	7.86

temperatures which were used to determine the values of the terms sTa4 (0.56 - 0.08v e1) and (e - e1)/10 corresponding to the measured dew point temperature means. These expressions are given in Table 3.7

A summarised working sheet for the computation of the evaporative demand (Ed) taken as the potential evapotranspiration, is given in Table 3.8

3.10 Crop Yield Values

The only quantity considered here was the dry grain yield at harvest. The dry matter growth was not monitored because of the small size nature of the plots. The fact that the method of sampling would be destructive would result in the continous depopulation of the plants in the plots which in turn would result in significant effects on the crop evapotranspiration from the individual plots. Besides, considering the definition of the crop susceptibility (CS) factors, only the dry grain yield would be of interest rather than the dry matter yield. Therefore, the crop was harvested manually between 16th and 19th March, 1992, after full maturity, by cutting and collecting all the crop in each plot. Threshing and sorting was also done manually and the weights of the grain yield for each plot was obtained using an electronic balance (Mettler PN1210). However, the yields presented in this report (See Table 3.9), which were also used for the analysis that follows, were the highest obtained for each treatment. This was necessary because of the effect of

Table 3.7: Expressions for the Computation of F and H Factors

Mean Air Temperature	F*	r^2	"H	r^2
16	$5.26 - 0.13T_{dp}$	0.999	$1.42 - 0.09T_{dp}$	0.996
18	$5.42 - 0.14T_{dp}$	0.998	$1.71 - 0.09T_{dp}$	0.989
19	$5.59 - 0.15T_{dp}$	0.998	$1.82 - 0.09T_{dp}$	0.989
20	$5.64 - 0.15T_{dp}$	0.997	$2.08 - 0.10T_{dp}$	0.986
21	$5.69 - 0.15T_{dp}$	0.997	$2.22 - 0.10T_{dp}$	0.985
22	$5.86 - 0.16T_{dp}$	0.997	$2.37 - 0.10T_{dp}$	0.983
23	$5.90 - 0.16T_{dp}$	0.997	$1.66 - 0.11T_{dp}$	0.982
24	$6.13 - 0.17T_{dp}$	0.996	$2.83 - 0.11T_{dp}$	0.979

* T_{dp} = Dew point temperature, while

* F gives values of δTa^4 $(0.56 - 0.08\sqrt{é})$, and

** H gives values of $(e - é) \times \frac{1}{10}$ in Eq. 2.14

Table 3.8: Summarised working Sheet for Evaporative Demand Computations

Period	A	B	C	ABC	D	E	F	DEF	G	H	J	GHJ	*Ed mm/day
1 - 7	11.73	0.742	0.71	6.18	0.724	0.81	6.06	3.55	0.75	2.77	1.48	3.08	5.71
8 -14	11.37	0.734	0.53	4.42	0.702	0.52	5.98	2.18	0.80	2.42	2.09	4.05	6.3
15-21	11.00	0.734	0.65	5.25	0.679	0.72	6.06	2.96	0.87	2.10	1.79	3.27	5.7
22-28	11.19	0.735	0.66	5.43	0.691	0.74	5.83	2.98	0.83	2.24	2.10	3.90	6.4
29-35	10.40	0.742	0.33	2.55	0.642	0.20	4.63	0.60	0.97	1.02	2.37	2.35	4.3
36-42	10.81	0.742	0.54	4.33	0.667	0.50	4.85	1.62	0.90	1.34	2.25	2.71	5.4
43-49	11.37	0.756	0.62	5.33	0.702	0.67	5.11	2.40	0.80	1.84	1.77	2.61	5.5
50-56	11.55	0.775	0.54	4.83	0.713	0.54	5.27	2.03	0.77	2.00	1.68	2.59	5.4
57-63	11.73	0.798	0.70	6.55	0.724	0.81	6.65	3.90	0.75	3.18	1.73	4.13	6.8
64-70	11.55	0.798	0.64	5.90	0.713	0.69	6.59	3.24	0.77	2.83	2.31	5.03	7.7
71-77	11.55	0.823	0.64	6.08	0.713	0.70	7.78	3.87	0.77	3.58	2.27	6.26	8.51
78-84	11.73	0.843	0.64	6.33	0.724	0.69	7.66	3.83	0.74	3.82	2.11	6.05	8.6

* Ed = (ABC) - (DEF) + (GHJ)

Table 3.9 Results of Grain Yields

Treatment	Grain Yield (tons ha-1)
C	1.38
SDI	1.34
AI	1.36
BI	1.28
CI	1.00
DI	0.56
AII	1.07
BII	0.89
CII	0.73
DII	0.44
AIII	1.23
BIII	1.05
CIII	0.79
DIII	0.47

pest attack on the crop observed during the ripening period. Thus, it was assumed that the plots with the highest yield for the treatments were the least affected. With this problem therefore, comparisons among the treatments and with the control in terms of the significance of the differences in the yields was made impossible statistically.

CHAPTER FOUR

EXPERIMENTAL RESULTS AND DISCUSSIONS

4.0 Introduction

The performance of any irrigation system or water management technique can be measured along different directions using various parameters as desired, depending on the prevailing local conditions and needs. Common among the various parameters that are often used in any irrigation system evaluation include water conservation, labour conservation and increase in crop yield.

The potentials of the Stress-Day Index concept in irrigation scheduling in terms of optimizing water use efficiency has already been shown by studies conducted by Hiler et al (1974). However, it has also been observed that the effectiveness of the concept in irrigation scheduling is influenced by the level of technology and the type of stress indicator used to characterise the Stress-Day (SD) factor (Hiler et al; 1974). Therefore, since most Nigerian farmers are technologically undeveloped for the practical adoption of the sophisticated Stress-Day characterisation that would ensure optimum results from the concept, it is important to test the possibility of using a system of characterising the Stress-Day factor that would be both practical, under our local situation, and yield results similar to those already reported. Thus, the discussion in this report is mostly centred on the

performance of a time-based stress indicator in the Stress-Day Index irrigation scheduling approach.

4.1 Soil Moisture Status

The soil moisture extraction levels for each treatment for the growth stages considered in the study, expressed as the volumetric soil moisture content were computed from Eq. 3.5 and are given in Table 4.1. This however, is better presented in terms of the soil suction since this gives the energy required to extract water from the soil by the plant which may not be obvious from the soil moisture content data, because the energy requirement may differ at the same soil moisture content for different soil types. Therefore, the soil suction values attained between irrigations were determined by reading the suction values, from the generated soil moisture characteristics' curves explained in section 3.2, corresponding to the measured soil moisture contents just before irrigations. It was however observed that at some points, the soil moisture content of the upper soil layer in some treatments dropped very much below the soil moisture content at wilting point, possibly due to direct evaporation from the soil. Thus, average values of soil suction based on the computed soil moisture content of the entire root zone profile would indicate that the crop would not extract any moisture from the soil since suction values above $15x10^5$ N/m^2

Table 4:1 : Average Volumetric Moisture Content for the 600-mm Depth Root Zone Just before each irrigation.

Treatment	Soil Moisture Content cm^3/cm^3																	
	January								Febuary									
	7	10	14	17	21	24	28	31	4	7	11	14	16	18	21	25	28	
C	0.2277	*	0.2031	-	0.1825	-	0.1743	-	0.1571	-	0.1481	-	-	0.1631	-	0.1733	-	
SDI	-	0.1960	-	-	0.1790	-	0.1882	-	0.1681	-	0.1636	-	0.1883	-	-	-	-	
AI	**/	-	-	0.1852	-	0.1875	-	0.1982	-	0.1845	-	0.1611	-	-	0.1617	-	0.1773	
BI	/	-	-	-	0.1617	-	0.1903	-	0.1869	-	0.1815	-	-	0.1833	-	0.1789	-	
CI	/	-	-	-	-	0.1585	-	0.1751	-	0.1676	-	0.1616	-	-	0.1672	-	0.1751	
DI	/	-	-	-	-	-	0.1406	-	0.1938	-	0.1939	-	-	0.1581	-	0.1699	-	
AII	/	-	/	-	/	-	-	0.16239	-	0.1575	-	0.1581	-	-	0.1571	-	0.1709	
BII	/	-	/	-	/	-	-	-	0.1520	-	0.1470	-	-	0.1560	-	0.1597	-	
CII	/	-	/	-	/	-	-	-	-	0.1329	-	0.1410	-	-	0.1467	-	0.1523	
DII	/	-	/	-	/	-	-	-	-	-	0.1314	-	-	0.1365	-	0.1434	-	
AIII	/	-	/	-	/	-	/	-	/	-	-	0.1529	-	-	0.1540	-	0.1667	
BIII	/	-	/	-	/	-	/	-	/	-	-	-	-	0.1421	-	0.1380	-	
CIII	/	-	/	-	/	-	/	-	/	-	-	-	-	-	0.1309	-	0.1238	
DIII	/	-	/	-	/	-	/	-	/	-	-	-	-	-	-	0.1022	-	

* - not taken

** / same as control treatment

were indicated at the said points. However, since the lower soil layers in the root zone were still within the available moisture range during these periods, it would be erroneous to conclude thus. Therefore, with the assumption that the crop is unable to extract soil moisture at/or beyond the wilting point, the soil suction values for the entire 600 mm root zone depth were estimated as the average values of 150 -mm layer values, using the wilting point suction value for a layer where it was observed that the suction for the layer equals or falls above the wilting point value. Also, for layers with soil moisture content above that at field capacity, the suction value at field capacity was used for that layer in computing the average for the root zone depth. The results obtained from this procedure are given in Table 4.2. And, the variation in soil suction with time for the control treatment is shown in Fig. 4.1.

It was observed that there was a general increase in the water depletion level attained bewteen irrigations from the time of seeding until a maximum was attained on the 11th January, 1992 (70 days after seeding). Thereafter, there was a general decline in the water depletion between irrigations. This variation, despite the constant irrigation interval maintained throughout the growing season, could be

Table 4:2 : Average Soil WAter Potentials for the 600-mm Depth Root Zone just before each irrigation.

Treatment	Soil Water Potential ( ) X10^5 N/m^2																	
	January							February				Febuary						
	7	10	14	17	21	24	28	31	4	7	11	14	16	18	21	25	28	
C	1.756	*	4.077	-	4.806	-	4.672	-	6.132	-	6.871	-	-	5.274	-	4.734	-	
SDI	-	4.072	-	-	4.437	-	4.319	-	4.967	-	4.955	-	4.160	-	4.111	-	-	
AI	**/	-	-	4.360	-	4.295	-	4.316	-	4.422	-	6.367	-	-	4.636	-	4.512	
BI	/	-	-	-	6.541	-	4.252	-	4.205	-	4.286	-	-	4.575	-	4.564	-	
CI	/	-	-	-	-	7.931	-	4.747	-	5.127	-	5.181	-	-	5.046	-	4.668	
DI	/	-	-	-	-	-	8.161	-	4.527	-	4.372	-	-	5.712	-	4.667	-	
AII	/	-	/	-	/	-	-	5.761	-	5.179	-	5.857	-	-	6.297	-	5.223	
BII	/	-	/	-	/	-	-	-	8.227	-	7.678	-	-	8.335	-	9.179	-	
CII	/	-	/	-	/	-	-	-	-	9.096	-	8.870	-	-	8.372	-	8.006	
DII	/	-	/	-	/	-	-	-	-	-	9.442	-	-	9.099	-	10.448	-	
AIII	/	-	/	-	/	-	/	-	/	-	-	7.106	-	-	6.247	-	5.035	
BIII	/	-	/	-	/	-	/	-	/	-	-	-	-	8.966	-	7.926	-	
CIII	/	-	/	-	/	-	/	-	/	-	-	-	-	-	10.583	-	12.627	
DIII	/	-	/	-	/	-	/	-	/	-	-	-	-	-	-	15.000	-	

* - not taken

** / same as control treatment

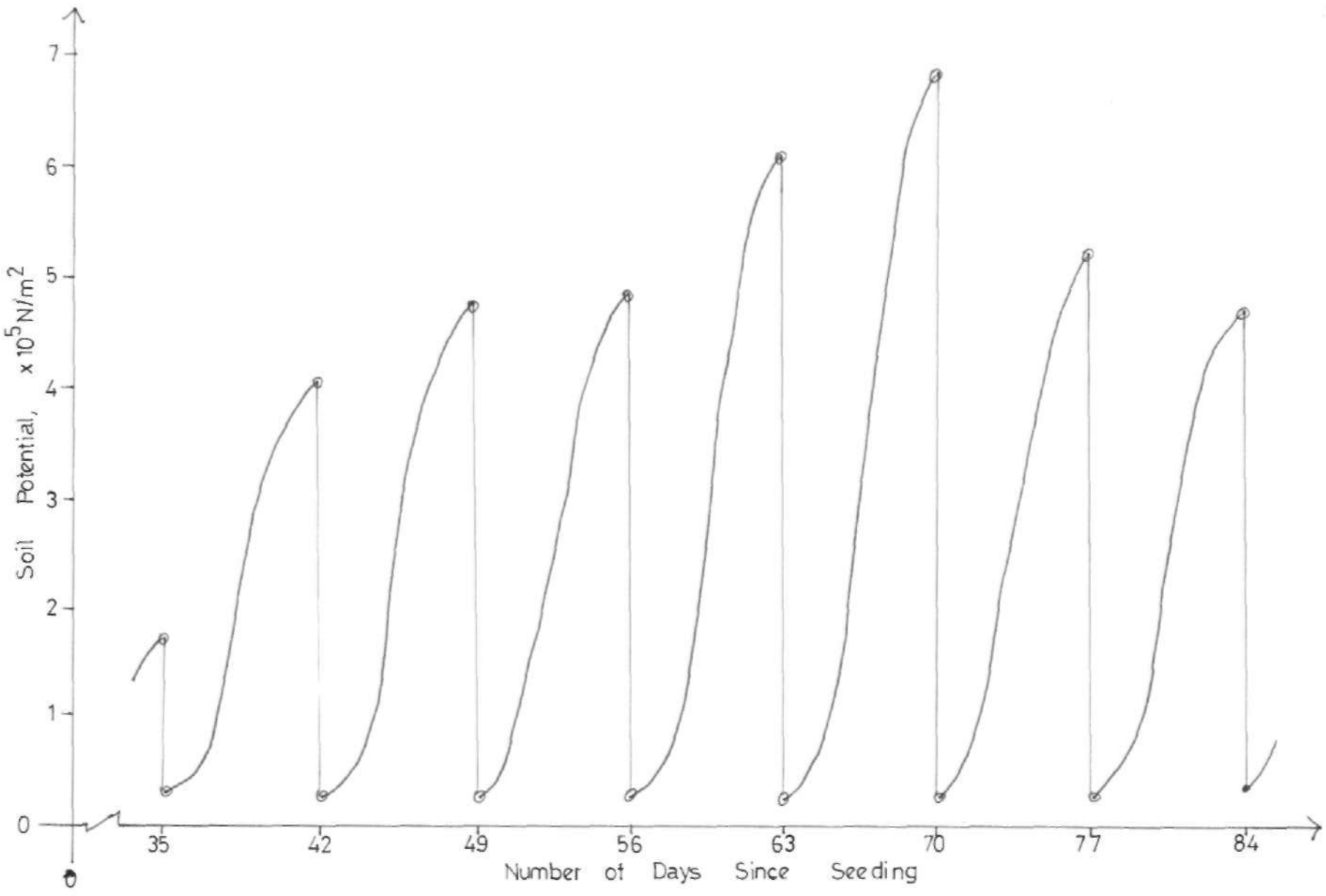


Fig. 4·1: Variation of Soil Water Potential With Time For The Control Treatment

Table 4.3 Estimated Actual Evapotranspiration Versus measured Evapotranspiration From Control Treatment.

Period (days from sedding)	Estimated potential Evapotran-spiration (mm/day)	*Crop coeffi-cient (Kc)	Estimated Actual Evapotran-spiration (mm/day)	Measured Evapotran-spiration (mm/day)
1 - 7	5.7	0.17	1.0	-
8 -14	6.3	0.36	2.3	-
15-21	5.7	0.43	2.5	-
22-28	6.4	0.53	3.4	-
29-35	4.3	0.66	2.8	1.9
36-42	5.4	0.84	4.5	3.3
43-49	5.5	0.99	5.4	4.7
50-56	5.4	1.02	5.5	5.5
57-63	6.8	0.85	5.8	7.0
64-70	7.7	0.80	6.2	7.8
71-77	8.5	0.57	4.9	6.4
78-84	8.6	0.35	3.0	5.6

* Source: Abdulmumin (1989)

Table 4.4 Measured Evapotranspiration Results

Treatment	Evapotranspiration, (mm)				Seasonal Evapotranspiration (mm)
	Growth Stage (days from seeding)				
	I (1 - 29	II (30 - 56)	III (57 - 69)	(70 - 84)	
C	56.4	107.2	103.4	84.3	351.3
SDI	56.4	92.9	84.6	53.5	287.4
AI	56.4	78.9	71.5	93.9	300.7
BI	56.4	70.9	65.5	69.2	264.0
CI	56.4	71.8	85.5	101.0	314.7
DI	56.4	53.1	56.2	87.6	253.3
AII	56.4	107.2	55.6	69.7	272.8
BII	56.4	107.2	68.5	104.1	292.4
CII	56.4	107.2	83.1	131.2	321.5
DII	56.4	107.2	51.1	118.6	276.9
AIII	56.4	107.2	103.4	95.5	306.1
BIII	56.4	107.2	103.4	64.1	274.7
CIII	56.4	107.2	103.4	79.3	289.9
DIII	56.4	107.2	103.4	82.0	292.6

Table 4.5 Measured Evapotranspiration During Stress Periods.

Treatment	Stress Period (days since seeding)	*ET_s (mm)	**ET_c (mm)
AI	43-45	9.3	14.0
BI	43-49	23.5	32.7
CI	43-52	27.2	49.3
DI	43-56	36.1	71.4
AII	57-59	6.8	21.0
BII	57-63	13.4	49.0
CII	57-66	24.8	72.3
DII	57.70	25.7	103.4
AIII	71-73	1.4	19.3
BIII	71-77	3.6	45.0
CIII	71-80	10.3	61.9
DIII	71-84	27.6	84.4

* ET_s = The measured evapotranspiration from the stressed treatment during stress periods.

** ET_c = The corresponding evapotranspiration from the control treatment during stress periods.

periods following a stress period, which agrees with the findings of Stewart et al. (1975).

4.3 Degree and Duration of Stress

The degree and duration of water stress in plants in the Stress-Day Index concept is indicated by the Stress-Day (SD) factor. As already discussed in section 2.5.1.1, a plant-based indicator should yield better results since they incorporate all the factors influencing plant stress. Therefore, the Stress-Day values for the stress periods of each of the stressed treatments were computed using a plant-based definition based on Eq. 2.17, and were compared with values obtained by a time-based Stress-Day definition, namely; the number of days between irrigations. In order to combine the degree and duration of crop water stress, Eq. 2.17 requires daily determination of soil moisture content, and since the soil moisture contents were determined only once during each stress period, the plant-based Stress-Day values were calculated for each stress period as (Mogenison, 1980):

$$SD_i = \left(1 - \frac{ET_s}{ET_c}\right)N \qquad \text{---------- 4.1}$$

with ETs as the evapotranspiration from the stressed treatments during a stress period, ETc the evapotranspiration from the control treatment during the same period and N the number of days of stress. The results of the computations are given in Table 4.6

Table 4.6 Computed Plant - Based Stress-Day Factors (SDp) for stressed Treatments

Treatment	Stress Period (days since seeding)	SDp
AI	43-45	1.01
BI	43-49	1.97
CI	43-52	4.48
DI	43-56	6.92
AII	57-59	2.03
BII	57-63	5.09
CII	57-66	6.57
DII	57.70	10.52
AIII	71-73	2.78
BIII	71-77	6.44
CIII	71-80	8.34
DIII	71-84	10.18

Table 4.6 indicate that there were differences in the stress imposed for the same reduction in irrigation. This can logically be attributed to the effects of changes in crop consumptive use and environmental conditions with the stage of growth of the crop as highlighted in Section 4.1. And, since it has been observed that the crop susceptibility (CS) factor is a function of the level and duration of stress permitted in its computation (Hiler et al; 1974; Stegman et al; 1980), it might lead to erroneous conclusions of the crop susceptibility factors if defined solely based on the number of days between irrigations as a stress indicator as this would imply defining the crop susceptibilities at different stress levels at the growth stages. For reliable crop susceptibility definition, the level of stress should be the same at the growth stages.

The effect of number of days of stress on the plant-based Stress-Day factor, as defined in Eq. 4.1 which henceforth will simply be referred to as plant-based Stress-Day factor in this report, at each growth stage is shown in Fig. 4.2. Thus, the number of days corresponding to a defined stress level could be obtained from Fig. 4.2 depending on the stage of growth of the crop.

4.4 Functional Relationship between Crop Susceptibility And Water Deficit

Hiler et al. (1974) observed that the principal

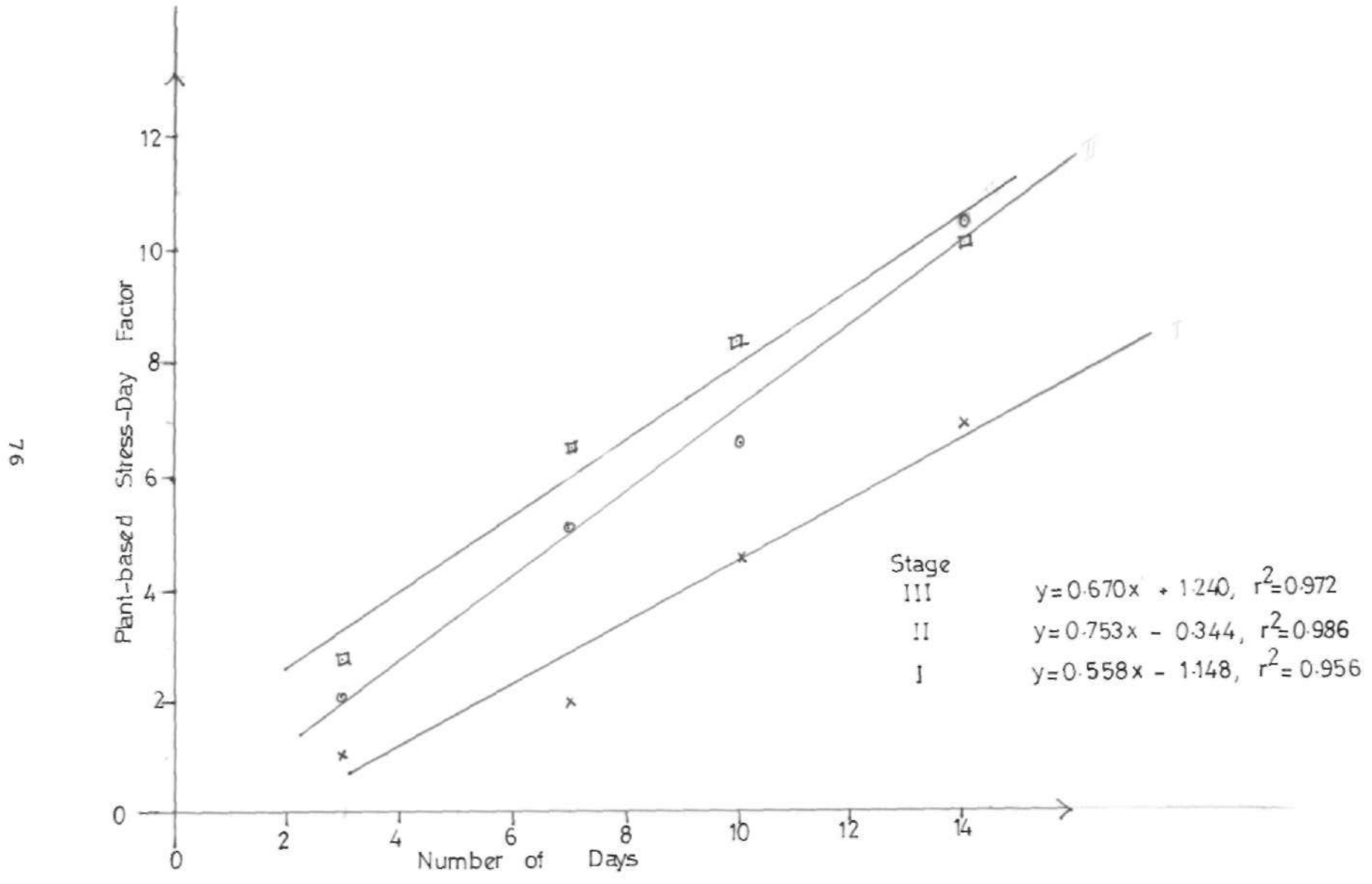


Fig. 4·2: Effect of Number of Days on Plant-based Stress-Days at The Three Growth Stages

advantage of the Stress-Day Index concept in irrigation scheduling would be quantification of the crop susceptibility (CS) factors. And, to be reasonably universal, such data should be gathered in dimensionless form, with the marketable yield expressed as a percentage of the maximum obtainable under the best soil conditions. However, a principal shortcoming of the irrigation scheduling approach is that the crop susceptibilities depend on the level of the water deficit permitted in their determination. Therefore, in order to precisely utilize the Stress-Day Index concept for irrigation scheduling, experiments are needed for which crop susceptibilities are determined not only as functions of crop species and growth stage but also as a function of the Stress-Day values as done for Southern Peas by Hiler et al. (1972).

The crop susceptibility factors in Table 4.7 were determined using Eq. 2.21 for each of the stressed treatments. The data were grouped according to the three growth stages considered and straight lines relating the crop susceptibilities and the plant-based Stress-Days were drawn as shown in Fig. 4.3.

From Fig. 4.3, it can be observed that, in general, the crop susceptibilities at a particular growth stage in relation to that of another growth stage depends on the level of stress imposed. That is, one growth stage might be more sensitive to stress at a

Table 4.7 Calculated Values of Crop Susceptibility Factors (CS)

Treatment	CS
C	-
SDI	-
AI	0.014
BI	0.075
CI	0.280
DI	0.597
AII	0.222
BII	0.360
CII	0.470
DII	0.675
AIII	0.110
BIII	0.241
CIII	0.431
DIII	0.656

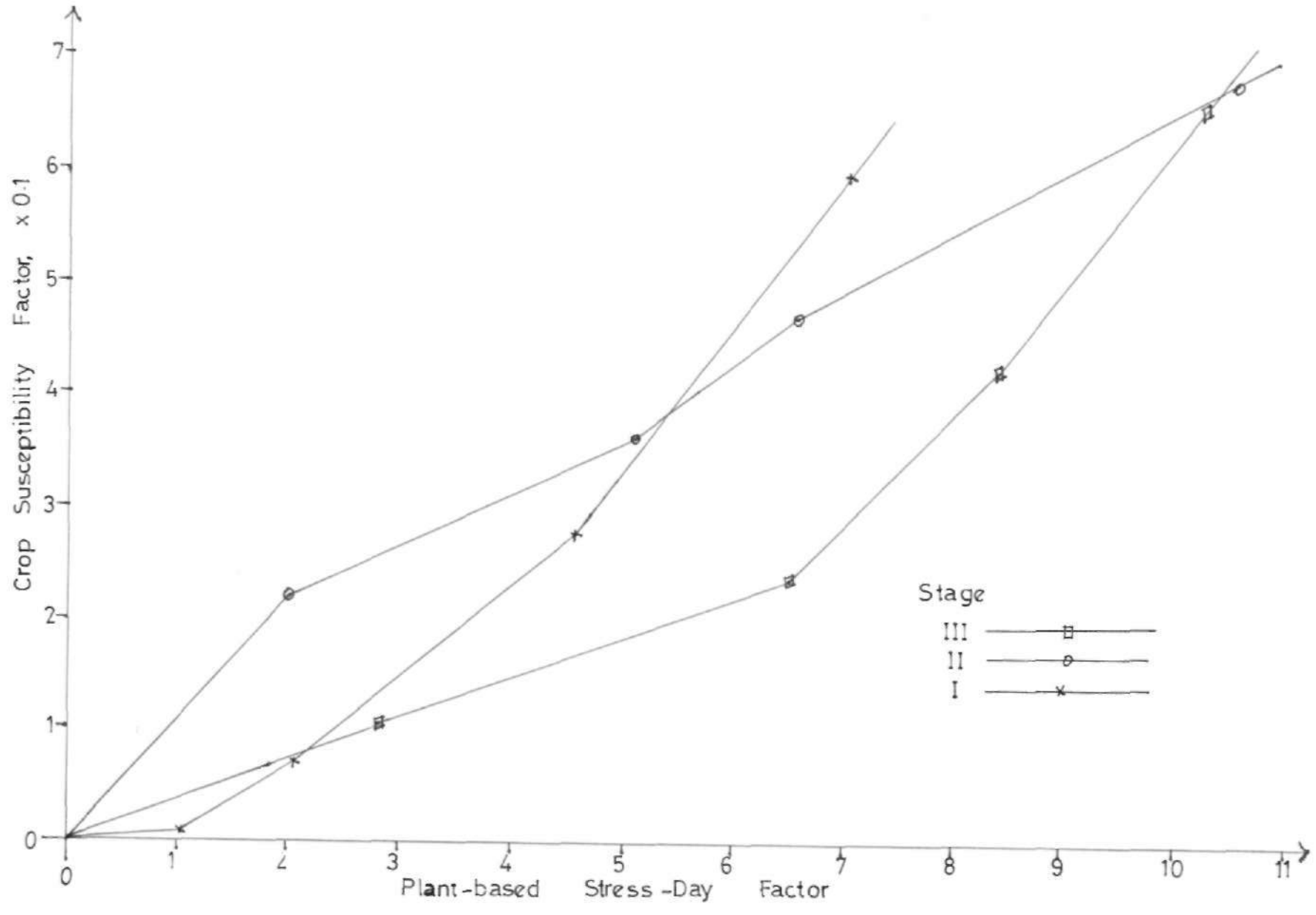


Fig. 4·3: Variation of Crop Susceptibility With Plant-based Stress-Day Factors

particular range of Stress-Days and another might be at another Stress-Day range. This could be the reason for the different conclusions reached by different researchers. For example, El Nadi (1969) found that, for wheat, the flowering to maturity stages are more sensitive to drought than the vegetation stage, and Salter and Goode (1967) concluded from examination of a large number of studies of cereal crops including wheat, that cereal crops seems especially sensitive to drought during shooting and earing stages. However, Day and Intalap (1970) found the jointing stage the most critical stage. In a review of different works, Datiri (1982) noted the complexity of the subject in view of the different conclusions redached.

Figure 4.3 provide a type of data required for a more precise utilization of the Stress-Day Index concept since it provides crop susceptibility values not only as a function of crop species and growth stage, but also as a function of the level of the water deficit. Therefore, at defined Stress-Days determined by the prevailing local conditions and needs, the corresponding crop susceptibility factor for each growth stage can be obtained from the relevant curve in Figure 4.3 for use in determining when to irrigate using the Stess-Day Index concept.

4.5 Water Use Efficiency

As discussed in section 2.4, the water use

efficiency (WUE) provides a measure of the crop's physiological response to water input. Omotowoju (1992) has identified optimum sequencing of water supply and adoption of efficient crop and soil management techniques as a means towards increasing water use efficiency.

Data from the Stress-Day Index treatment showed a 20.5 percent increase in water use efficiency over the control treatment (See Table 4.8). The water use efficiency values were calculated from Eq. 2.15. The results were found to be similar to those obtained by Hiler et al (1974), where the increase in the water use efficiency was predominantly due to reduction in evapotranspiration amounts rather than increase in yield. It is however unfortunate that no statistical analysis could be conducted to ascertain the signfificance of this increase in water use efficiency because of the shortcoming already mentioned in section 3.10.

Nonetheless, in agreement with Dudley et al. (1971), the Stress-Day Index concept would appear to have application in optimization models which seek to optimise water allocation for irrigation. This seems also true with the time-based Stress-Day characterisation as indicated by the results.

By the time - based stress-Day Index approach to irrigation scheduling, a water savings of 639m^3/ha was realised without any appreciable decrease in grain

Table 4.8 Seasonal Evapotranspiration Grain Yield, And Water Use Efficiency (WUE) Results

Treatment	Seasonal Evapotranspiration (mm)	Grain Yield (tons/ha)	WUE (tons/ha/mm) $X10^{-3}$
C	351.3	1.39	3.9
SDI	287.4	1.34	4.7
AI	300.7	1.36	4.5
BI	264.0	1.28	4.8
CI	314.7	1.00	3.2
DI	253.3	0.56	2.2
AII	272.8	1.07	3.9
BII	292.4	0.89	3.0
CII	321.5	0.73	2.3
DII	276.9	0.45	1.6
AIII	306.1	1.23	4.0
BIII	274.7	1.05	3.8
CIII	289.9	0.79	2.7
DIII	292.6	0.47	1.6

yield. It would appear therefore, that the time-based Stress-Day Index concept could be utilized in conjunction with the local conventional approach to irrigation scheduling which is based on crop consumptive use, provided reliable crop susceptibility factors are available for use in the concept. Thus, the Stress-Day factor could be characterised by the number of days between irrigations as determined by the crop consumptive use and then used to determine the actual time of irrigation using the format shown in Table 3.4 employing the appropriate crop susceptibility factors corresponding to the growth stages of the crop, to yield improved water use efficiency results in irrigation systems.

4.6 Functional Relationship Between Stress-Day Index And Grain Yield

Besides its use in optimizing irrigation scheduling, the stress-Day Index concept is useful in predicting crop yields for given crop water stress conditions. That is, given that all factors other than crop water stress which affect crop yield do not change significantly, expressions relating stress-Day Index and crop yield can be used to predict crop yields for known crop water stress conditions.

Comparing five different stress-Day characterisations, Hiler et al (1974) observed that the best method of characterising the stress-Day factor was indicated by a high correlation coefficient of the

linear regression between the seasonal stress-Day Index and marketable yield. Therefore, this parameter was determined using the results from the time based stress-Day characterisation. Using the crop susceptibility factors for the three growth stages considered, as given in Table 4.7, and the stress-Day factors defined as the number of days for which irrigation was delayed in excess of the control's 7-Day irrigation interval, the stress-Day Index values were calculated for each treatment using Eq. 2.16. By this analysis, it was observed that the time-based stress-Day indicator is suitable for characterizing water deficit since it gave a high correlation coefficient of 0.965. Figure 4.4 shows the best line relating seasonal stress-Day Index and grain yield.

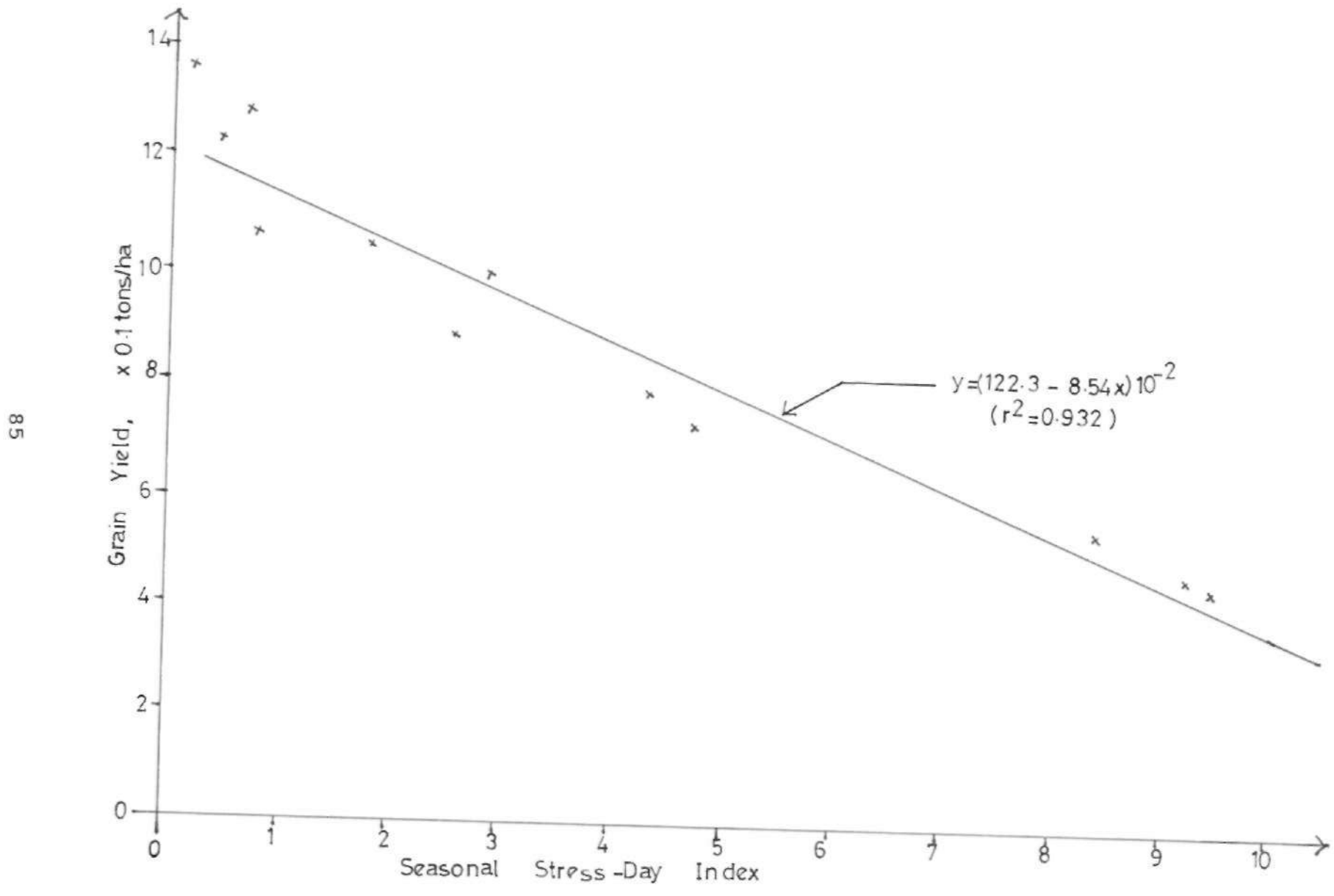


Fig. 4.4: Seasonal Stress-Day Index Versus Grain Yield

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

This study was aimed at evaluating the performance of a time-based Stress-Day Index approach to irrigation scheduling by formulating a criterion for irrigation by the Stress-Day Index concept first developed by Hiler (1969) using a time-based form of Stress-Day characterisation, namely; the irrigation interval.

An experiment was conducted during the 1991/92 irrigation season at the Ahmadu Bello University Farm, using wheat (Titicum aestivum L.) as the experimental crop. The irrigation treatments consisted of a "well-watered" control, irrigated at 7-day intervals following the local irrigation scheduling practice, a variable irrigation interval in three selected growth periods (Stress-Day Index treatments) and twelve additional treatments, named, the stressed treatments, with four levels of water deficit occuring once in three selected growth periods of the test crop. The four levels of water deficit were achieved by delaying irrigation by 3,7,10 and 14 days respectively in excess of the 'normal' 7-day irrigation interval.

Soil moisture measurements were made to determine actual crop evapotranspiration for each treatment, and hence irrigation amounts for the treatments, from which total crop water use was determined. Meteorological

data obtained from the Institute for Agricultural Research, Samaru were used to calculate the evaporative demand by the Penman evaporation estimate using the procedure detailed by Mc Culluch and EAAFRO (1965) for the rapid computation of the Penman evaporation estimate. The crop response measurement was only the grain yield at harvest.

It was observed from the experimental results that there was an increase in water use efficiency with the Stress-Day irrigation interval treatment over the conventional fixed-period irrigation interval treatment as a result of reduced seasonal crop water use. This increase in water use efficiency is expected because the Stress-Day Index treatment accounts for differing crop susceptibilities to water deficits at different stages of growth.

Results from the stressed treatments, in conjunction with those from the control were used to obtain crop susceptibility factor data as functions of plant water deficit levels and growth stage for the test crop.

5.2 Conclusions

For the conditions of this study, the results presented herein show that the following conclusions can be drawn:

(1) The time-based Stress-Day Index irrigation scheduling approach offers considerable promise for increasing

water use efficiency in irrigated agriculture except for the determination of the crop susceptibility factors.

(2) Due to changes in crop cunsumptive use and environmental conditions during the growth period, a time-based form of plant water deficit characterisation is less effective with regard to the definition of crop susceptibilities as a function of the timing of occurence of the deficit.

(3) The magnitude of a water deficit was found to be critical with regard to the definition of crop susceptibilities as a function of the timing of the occurence of the water deficit. For example, while one growth stage might show more sensitivity to water stress at a particular level of water deficit, another might be more sensitive at a different water deficit level. This therefore makes it difficult to advance a unifying theory of crop susceptibility factors as a function of only the growth stage.

(4) A linear relationship between Stress-Day Index and yield was indicated by a high correlation coefficient value for the graphs of Stress-Day Index versus yield for the time-based Stress-Day characterisation, suggesting the suitability of the time-based Stress-Day Index concept for use both for irrigation scheduling and for predicting crop yields at given stress conditions.

5.3 Recommendations

On the basis of the results obtained in this study, the following recommendations can be made:

(1) Given reliable crop susceptibility factors, the time-based Stress-Day Index concept for irrigation scheduling is strongly recommended for adoption in places where waterlogging problems exist such as the Kadawa Sector of the Kano River Project, as the concept show promise in improving water use efficiency.

(2) Thorough studies should be carried out that would yield reliable crop susceptibility factors as functions of crop species, growth stage and the level of water deficit for use in the time-based Stress-Day Index irrigation scheduling approach. These studies should be done using facilities to obtain more accurately all plant water dependant factors as a means of assessing the level of water deficit (based on the physical theory of water flow in the soil-plant -atmosphere continum) in the crop susceptibility computations.

(3) Since there was no statistical analysis conducted for this study to ascertain the extent of the time-based Stress-Day Index concept's superiority over the conventional irrigation scheduling approach, this experiment should be replicated over time and space in order to authenticate the findings of this study and possibly expand the

findings.

(4) Similar experiments are also recommended for other crops especially the major irrigated crops in the irrigation schemes, for the provision of the necessary data needed for implementing the Stress-Day Index irrigation scheduling approach.

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APPENDIX A:

A Decimal Code For The Growth Stages of Cereals.

A decimal code for the growth stages. Secondary growth stages

2-digit code	General description	Feekes' scale	Additional remarks on wheat, barley, rye, and oats
0	*Germination*		
00	Dry seed		
01	Start of imbibition		
02	—		
03	Imbibition complete		
04	—		
05	Radicle emerged from caryopsis		
06	—		
07	Coleoptile emerged from caryopsis		
08	—		
09	Leaf just at coleoptile tip		
1	*Seedling growth*		
10	First leaf through coleoptile	1	
11	First leaf unfolded*		Second leaf visible (< 1 cm)
12	2 leaves unfolded		50 % of laminae unfolded
13	3 leaves unfolded		
14	4 leaves unfolded		
15	5 leaves unfolded		
16	6 leaves unfolded		
17	7 leaves unfolded		
18	8 leaves unfolded		
19	9 or more leaves unfolded		
2	*Tillering*		
20	Main shoot only		
21	Main shoot and 1 tiller	2	
22	Main shoot and 2 tillers		This section to be used to supplement records from other sections of the table: 'concurrent codes'
23	Main shoot and 3 tillers		
24	Main shoot and 4 tillers		
25	Main shoot and 5 tillers		
26	Main shoot and 6 tillers	3	
27	Main shoot and 7 tillers		
28	Main shoot and 8 tillers		
29	Main shoot and 9 or more tillers		
3	*Stem elongation*		
30	Pseudo stem erection†	4–5	In rice: vegetative lag phase
31	1st node detectable	6	Jointing stage
32	2nd node detectable	7	Jointing stage
33	3rd node detectable		Above-crown nodes
34	4th node detectable		
35	5th node detectable		
36	6th node detectable		
37	Flag leaf just visible	8	
38	—		
39	Flag leaf ligule/collar just visible	9	Pre-boot stage In rice: opposite auricle stage
4	*Booting*		
40	—		
41	Flag leaf sheath extending		Little enlargement of the inflorescence, early-boot stage
42	—		
43	Boots just visibly swollen		Mid-boot stage
44	—		
45	Boots swollen	10	Late-boot stage
46	—		
47	Flag leaf sheath opening		
48	—		
49	First awns visible		In awned forms only

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A decimal code for the growth stages. Secondary growth stages (*contd.*)

2-digit code	General description		Feekes' scale	Additional remarks on wheat, barley, rye, and oats
5	*Inflorescence emergence*			
50	First spikelet of inflorescence just visible	N	10·1	N = non-synchronous crops; S = synchronous crops — see text
51		S		
52	¼ of inflorescence emerged	N	10·2	
53		S		
54	½ of inflorescence emerged	N	10·3	
55		S		
56	¾ of inflorescence emerged	N	10·4	
57		S		
58	Emergence of inflorescence completed	N	10·5	
59		S		
6	*Anthesis*			
60	Beginning of anthesis	N	10·51	Not easily detectable in barley. In rice: usually immediately following heading
61		S		
62	—			
63	—			
64	Anthesis half-way	N		
65		S		
66	—			
67	—			
68	Anthesis complete	N		
69		S		
7	*Milk development*			
70	—			
71	Caryopsis water ripe		10·54	
72	—			
73	Early milk		11·1	Increase in solids of liquid endosperm notable when crushing the caryopsis between fingers
74	—			
75	Medium milk			
76	—			
77	Late milk			
78	—			
79	—			
8	*Dough development*			
80	—			
81	—			
82	—			
83	Early dough		11·2	Finger nail impression not held
84	—			
85	Soft dough			
86	—			
87	Hard dough			Finger nail impression held, inflorescence loosing chlorophyl
88	—			
89	—			
9	*Ripening*			
90	—			In rice: terminal spikelets ripened
91	Caryopsis hard (difficult to divide by thumb-nail)‡		11·3	In rice: 50 per cent of spikelets ripened
92	Caryopsis hard (can no longer be dented by thumb-nail)§		11·4	In rice: over 90 per cent of spikelets ripened**
93	Caryopsis loosening in daytime			
94	Over-ripe, straw dead and collapsing			
95	Seed dormant			
96	Viable seed giving 50 % germination			
97	Seed not dormant			
98	Secondary dormancy induced			
99	Secondary dormancy lost			

APPENDIX B :

Soil Moisture Content Measurements.

Appendix B: Soil Moisture Content Measurements

Treatment	Soil layer (cm)	Soil Moisture Content, g/g %																		
		January							February											
		7	10	14	17	21	24	28	31	4	7	11	14	15	18	21	25	28		
C	0 - 15	9.48	-	7.00	-	7.14	-	4.95	-	4.87	-	4.31	-	-	4.93	-	5.86	-		
	15 - 30	17.08	-	14.05	-	11.48	-	11.39	-	10.50	-	10.31	-	-	11.21	-	12.73	-		
	30 - 45	18.67	-	17.86	-	16.78	-	15.65	-	13.77	-	13.80	-	-	14.38	-	14.14	-		
	45 - 60	19.75	-	19.27	-	17.41	-	18.31	-	16.14	-	14.49	-	-	16.62	-	16.95	-		
SDI	0 - 15	-	5.56	-	-	5.01	-	6.96	-	5.43	-	5.40	-	5.11	-	7.31	-	-		
	15 - 30	-	14.07	-	-	12.51	-	13.25	-	11.92	-	11.76	-	13.72	-	13.93	-	-		
	30 - 45	-	17.81	-	-	16.20	-	15.92	-	14.26	-	14.55	-	16.85	-	17.68	-	-		
	45 - 60	-	18.95	-	-	17.83	-	17.82	-	16.73	-	16.44	-	18.53	-	19.91	-	-		
AI	0 - 15	/	-	-	6.08	-	6.60	-	6.96	-	6.72	-	5.52	-	-	6.67	-	6.26		
	15 - 30	/	-	-	12.75	-	13.14	-	13.35	-	13.01	-	10.37	-	-	12.15	-	12.79		
	30 - 45	/	-	-	16.32	-	14.74	-	15.95	-	15.62	-	13.19	-	-	15.65	-	15.35		
	45 - 60	/	-	-	18.09	-	18.38	-	17.82	-	17.78	-	17.39	-	-	17.15	-	17.09		
CI	0 - 15	/	-	-	-	3.89	-	6.87	-	5.41	-	5.11	-	-	7.30	-	6.38	-		
	15- 30	/	-	-	-	9.90	-	13.54	-	13.68	-	13.72	-	-	12.27	-	12.61	-		
	30- 45	/	-	-	-	15.37	-	16.40	-	16.66	-	16.85	-	-	15.22	-	15.15	-		
	45- 60	/	-	-	-	17.64	-	17.74	-	17.98	-	17.52	-	-	17.78	-	17.22	-		
DI	0 - 15	/	-	-	-	-	3.59	-	5.69	-	5.28	-	4.22	-	-	5.21	-	5.24		
	15- 30	/	-	-	-	-	8.99	-	11.62	-	11.32	-	11.41	-	-	11.57	-	11.98		
	30- 45	/	-	-	-	-	15.35	-	15.62	-	14.90	-	14.44	-	-	14.59	-	15.68		
	45- 60	/	-	-	-	-	17.12	-	17.24	-	16.74	-	16.54	-	-	16.74	-	17.39		
								2.73	-	9.21	-	9.11	-	-	4.69	-	4.99	-		
								7.25	-	13.38	-	13.82	-	-	11.22	-	12.61	-		
								14.20	-	15.18	-	15.43	-	-	13.12	-	15.21	-		
								16.75	-	16.31	-	16.92	-	-	16.56	-	17.12	-		

Appendix B Continued

Treatment	Soil layer (cm)	Soil Moisture Content, g/g %																	
		January							February										
		7	10	14	17	21	24	28	31	4	7	11	14	16	18	21	25	28	
AII	0 - 15	/	-	/	-	/	-	-	4.80	-	3.22	-	3.69	-	-	5.82	-	7.18	
	15- 30	/	-	/	-	/	-	-	10.54	-	11.47	-	10.43	-	-	10.74	-	11.69	
	30- 45	/	-	/	-	/	-	-	15.15	-	14.26	-	16.98	-	-	13.05	-	13.91	
	45- 60	/	-	/	-	/	-	-	16.43	-	16.61	-	16.61	-	-	15.51	-	16.16	
BII	0 - 15	/	-	/	-	/	-	-	-	4.27	-	3.66	-	-	6.10	-	5.06	-	
	15- 30	/	-	/	-	/	-	-	-	9.23	-	9.59	-	-	8.65	-	9.29	-	
	30- 45	/	-	/	-	/	-	-	-	14.57	-	13.02	-	-	13.71	-	12.31	-	
	45- 60	/	-	/	-	/	-	-	-	15.78	-	16.30	-	-	16.45	-	14.06	-	
CII	0 - 15	/	-	/	-	/	-	-	-	-	2.31	-	3.19	-	-	3.34	-	4.08	
	15- 30	/	-	/	-	/	-	-	-	-	8.33	-	7.61	-	-	8.59	-	8.41	
	30- 45	/	-	/	-	/	-	-	-	-	12.56	-	12.51	-	-	13.35	-	14.83	
	45- 60	/	-	/	-	/	-	-	-	-	15.46	-	17.21	-	-	17.35	-	17.06	
DII	0 - 15	/	-	/	-	/	-	-	-	-	-	2.92	-	-	2.38	-	5.95	-	
	15- 30	/	-	/	-	/	-	-	-	-	-	6.99	-	-	8.60	-	8.08	-	
	30- 45	/	-	/	-	/	-	-	-	-	-	11.82	-	-	12.38	-	11.37	-	
	45- 60	/	-	/	-	/	-	-	-	-	-	16.58	-	-	16.18	-	15.96	-	
AIII	0 - 15	/	-	/	-	/	-	/	-	/	-	-	3.75	-	-	4.48	-	5.72	
	15- 30	/	-	/	-	/	-	/	-	/	-	-	9.77	-	-	10.52	-	12.31	
	30- 45	/	-	/	-	/	-	/	-	/	-	-	12.29	-	-	13.48	-	14.12	
	45- 60	/	-	/	-	/	-	/	-	/	-	-	16.40	-	-	15.92	-	15.68	
BIII	0 - 15	/	-	/	-	/	-	/	-	/	-	-	-	-	-	3.40	-	3.82	
	15- 30	/	-	/	-	/	-	/	-	/	-	-	-	-	-	8.03	-	9.46	
	30- 45	/	-	/	-	/	-	/	-	/	-	-	-	-	-	12.52	-	12.06	
	45- 60	/	-	/	-	/	-	/	-	/	-	-	-	-	-	16.71	-	16.51	

Appendix B Continued

Treatment	Soil layer (cm)	Soil Moisture Content, g/g %																
		January							February									
		7	10	14	17	21	24	28	31	4	7	11	14	16	18	21	25	28
CIII	0 - 15	/	-	/	-	/	-	/	-	/	-	-	-	-	-	3.53	-	3.32
	15- 30	/	-	/	-	/	-	/	-	/	-	-	-	-	-	8.66	-	8.64
	30- 45	/	-	/	-	/	-	/	-	/	-	-	-	-	-	11.65	-	11.16
	45- 60	/	-	/	-	/	-	/	-	/	-	-	-	-	-	13.98	-	12.59
DIII	0 - 15	/	-	/	-	/	-	/	-	/	-	-	-	-	-	2.66	-	
	15- 30	/	-	/	-	/	-	/	-	/	-	-	-	-	-	6.17	-	
	30- 45	/	-	/	-	/	-	/	-	/	-	-	-	-	-	8.76	-	
	45- 60	/	-	/	-	/	-	/	-	/	-	-	-	-	-	11.83	-	

* - not taken
** / same as control treatment

APPENDIX C:

Tables For The Rapid Computation of The Penman Estimate of Evapotranspiration.

TABLE A—VALUES OF $\left(\frac{\Delta}{\Delta+\gamma}\right)\left(\frac{1-r}{L}\right)$ FOR $r = 5\%$. TABLE D—VALUES OF $\left(\frac{\Delta}{\Delta+\gamma}\right)$ TABLE G—VALUES OF $0{\cdot}26\left(1+\frac{h}{20{,}000}\right)\left(\frac{\gamma}{\Delta+\gamma}\right)\times 10$.

Mean Air Temperature °C	Altitude h in Metres																					
	0			500			1,000			1,500			2,000			2,500			3,000			
	A	D	G	A	D	G	A	D	G	A	D	G	A	D	G	A	D	G	A	D	G	
5	7·61	0·470	1·38	7·84	0·484	1·39	8·10	0·500	1·35	8·34	0·515	1·36	8·59	0·530	1·36	8·85	0·546	1·32	9·09	0·561	1·32	5
6	7·86	0·485	1·34	8·10	0·500	1·35	8·34	0·515	1·31	8·59	0·530	1·32	8·83	0·545	1·32	9·09	0·561	1·27	9·33	0·576	1·27	6
7	8·10	0·500	1·30	8·34	0·515	1·31	8·59	0·530	1·27	8·83	0·545	1·27	9·07	0·560	1·28	9·33	0·576	1·23	9·57	0·591	1·23	7
8	8·34	0·515	1·26	8·59	0·530	1·27	8·83	0·545	1·23	9·07	0·560	1·23	9·32	0·575	1·23	9·57	0·591	1·19	9·80	0·605	1·18	8
9	8·59	0·530	1·22	8·83	0·545	1·23	9·07	0·560	1·19	9·32	0·575	1·19	9·56	0·590	1·19	9·80	0·605	1·15	10·03	0·619	1·14	9
10	8·83	0·545	1·18	9·07	0·560	1·18	9·30	0·574	1·15	9·54	0·589	1·15	9·78	0·604	1·15	10·03	0·619	1·10	10·25	0·633	1·10	10
11	9·05	0·559	1·15	9·30	0·574	1·15	9·54	0·589	1·11	9·77	0·603	1·11	10·01	0·618	1·11	10·25	0·633	1·06	10·48	0·647	1·06	11
12	9·30	0·574	1·11	9·53	0·588	1·11	9·77	0·603	1·07	10·00	0·617	1·07	10·24	0·632	1·07	10·47	0·646	1·03	10·69	0·660	1·02	12
13	9·53	0·588	1·07	9·75	0·602	1·07	9·98	0·616	1·04	10·22	0·631	1·03	10·45	0·645	1·03	10·68	0·659	0·99	10·90	0·673	0·98	13
14	9·75	0·602	1·03	9·98	0·616	1·04	10·21	0·630	1·00	10·43	0·644	1·00	10·66	0·658	0·99	10·89	0·672	0·95	11·10	0·685	0·94	14
15	9·96	0·615	1·00	10·19	0·629	1·00	10·42	0·643	0·96	10·64	0·657	0·96	10·87	0·671	0·95	11·10	0·685	0·91	11·29	0·697	0·91	15
16	10·17	0·628	0·97	10·40	0·642	0·97	10·63	0·656	0·93	10·85	0·670	0·92	11·06	0·683	0·92	11·28	0·696	0·88	11·49	0·709	0·87	16
17	10·38	0·641	0·93	10·61	0·655	0·93	10·84	0·669	0·89	11·05	0·682	0·89	11·26	0·695	0·88	11·47	0·708	0·85	11·68	0·721	0·84	17
18	10·59	0·654	0·90	10·81	0·667	0·90	11·02	0·680	0·86	11·24	0·694	0·86	11·45	0·707	0·85	11·66	0·720	0·81	11·86	0·732	0·80	18
19	10·79	0·666	0·87	11·00	0·679	0·87	11·23	0·693	0·83	11·42	0·705	0·83	11·63	0·718	0·82	11·83	0·730	0·78	12·04	0·743	0·77	19
20	10·98	0·678	0·84	11·19	0·691	0·83	11·40	0·704	0·80	11·60	0·716	0·80	11·81	0·729	0·79	12·00	0·741	0·75	12·20	0·753	0·74	20
21	11·18	0·690	0·81	11·37	0·702	0·80	11·58	0·715	0·77	11·78	0·727	0·76	11·97	0·739	0·76	12·17	0·751	0·72	12·36	0·763	0·71	21
22	11·36	0·701	0·78	11·55	0·713	0·77	11·76	0·726	0·74	11·96	0·738	0·73	12·13	0·749	0·73	12·33	0·761	0·69	12·51	0·772	0·68	22
23	11·53	0·712	0·75	11·73	0·724	0·75	11·92	0·736	0·71	12·12	0·748	0·71	12·30	0·759	0·70	12·49	0·771	0·66	12·65	0·781	0·66	23
24	11·71	0·723	0·72	11·89	0·734	0·72	12·09	0·746	0·69	12·28	0·758	0·68	12·46	0·769	0·67	12·64	0·780	0·64	12·80	0·790	0·63	24
25	11·87	0·733	0·69	12·05	0·744	0·69	12·25	0·756	0·66	12·43	0·767	0·65	12·60	0·778	0·64	12·78	0·789	0·61	12·94	0·799	0·60	25
26	12·04	0·743	0·67	12·21	0·754	0·66	12·39	0·765	0·63	12·57	0·776	0·63	12·75	0·787	0·62	12·91	0·797	0·59	13·07	0·807	0·58	26
27	12·20	0·753	0·64	12·38	0·764	0·64	12·56	0·775	0·61	12·72	0·785	0·60	12·88	0·795	0·59	13·04	0·805	0·57	13·20	0·815	0·56	27
28	12·34	0·762	0·62	12·52	0·773	0·61	12·70	0·784	0·58	12·85	0·793	0·58	13·01	0·803	0·57	13·17	0·813	0·54	13·32	0·822	0·53	28
29	12·49	0·771	0·60	12·65	0·781	0·59	12·83	0·792	0·56	12·98	0·801	0·56	13·14	0·811	0·55	13·30	0·821	0·52	13·46	0·831	0·51	29
30	12·64	0·780	0·57	12·80	0·790	0·57	12·96	0·800	0·54	13·11	0·809	0·53	13·27	0·819	0·52	13·41	0·828	0·50	13·54	0·836	0·49	30
31	12·78	0·789	0·55	12·93	0·798	0·55	13·09	0·808	0·52	13·24	0·817	0·51	13·38	0·826	0·50	13·53	0·835	0·48	13·66	0·843	0·47	31
32	12·91	0·797	0·53	13·06	0·806	0·52	13·20	0·815	0·50	13·35	0·824	0·49	13·49	0·833	0·48	13·64	0·842	0·46	13·77	0·850	0·45	32
33	13·02	0·804	0·51	13·17	0·813	0·50	13·33	0·823	0·48	13·46	0·831	0·47	13·61	0·840	0·46	13·74	0·848	0·44	13·87	0·856	0·43	33
34	13·15	0·812	0·49	13·28	0·820	0·49	13·45	0·830	0·46	13·58	0·838	0·45	13·71	0·846	0·45	13·83	0·854	0·42	13·96	0·862	0·41	34
35	13·27	0·819	0·47	13·40	0·827	0·47	13·54	0·836	0·44	13·67	0·844	0·44	13·80	0·852	0·43	13·93	0·860	0·41	14·05	0·867	0·40	35

TABLE B.—SOLAR RADIATION ON A HORIZONTAL SURFACE AT THE TOP OF THE ATMOSPHERE, Ra, FOR LATITUDES φ FROM 0–60° N. AND S. IN CAL/SQ.CM./DAY × 1/1,000

10-Day Periods	0°	10° N.	20° N.	30° N.	40° N.	50° N.	60° N.	10° S	20° S.	30° S.	40° S.	50° S.	60° S.
January I	·850	·742	·617	·429	·337	·184	·064	·934	·998	1·032	1·045	1·035	1·021
II	·858	·756	·636	·476	·361	·213	·082	·937	·990	1·018	1·023	1·003	·997
III	·868	·775	·662	·533	·399	·250	·110	·938	·980	·998	·991	·958	·914
February I	·879	·798	·693	·574	·446	·298	·155	·935	·965	·968	·945	·899	·833
II	·888	·823	·730	·622	·499	·357	·212	·929	·944	·930	·893	·830	·743
III	·894	·843	·763	·665	·547	·414	·270	·922	·921	·892	·840	·761	·661
March I	·898	·860	·794	·709	·600	·476	·336	·910	·893	·848	·780	·686	·577
II	·897	·876	·826	·754	·658	·543	·411	·892	·859	·799	·717	·609	·488
III	·891	·888	·853	·795	·714	·608	·487	·871	·822	·750	·653	·539	·406
April I	·882	·895	·878	·836	·764	·681	·573	·845	·781	·695	·585	·463	·324
II	·870	·897	·899	·873	·816	·751	·657	·818	·738	·640	·520	·389	·249
III	·854	·896	·913	·902	·866	·810	·730	·792	·700	·592	·467	·330	·192
May I	·838	·892	·922	·928	·905	·861	·800	·763	·663	·547	·417	·279	·145
II	·822	·887	·929	·949	·940	·909	·864	·734	·630	·506	·371	·235	·105
III	·808	·883	·933	·963	·964	·947	·917	·713	·602	·474	·338	·202	·075
June I	·797	·878	·934	·972	·982	·972	·956	·697	·581	·450	·314	·179	·056
II	·792	·874	·935	·976	·990	·984	·975	·689	·571	·438	·300	·167	·048
III	·791	·873	·935	·974	·989	·986	·975	·689	·568	·438	·299	·167	·048
July I	·795	·875	·934	·968	·981	·975	·958	·695	·576	·448	·309	·178	·057
II	·802	·878	·930	·958	·965	·951	·924	·707	·593	·466	·328	·197	·073
III	·812	·881	·925	·944	·942	·917	·876	·726	·616	·492	·357	·224	·097
August I	·827	·883	·917	·924	·910	·871	·814	·749	·646	·528	·398	·264	·132
II	·842	·886	·906	·900	·869	·812	·743	·774	·681	·572	·448	·316	·179
III	·858	·886	·894	·871	·823	·742	·668	·800	·720	·620	·503	·374	·236
September I	·870	·883	·874	·835	·770	·678	·584	·827	·763	·672	·568	·441	·305
II	·880	·876	·848	·794	·715	·616	·499	·854	·805	·727	·633	·513	·383
III	·886	·867	·823	·754	·662	·552	·423	·876	·839	·779	·692	·582	·462
October I	·888	·853	·794	·710	·605	·486	·348	·895	·872	·831	·753	·659	·550
II	·886	·836	·761	·662	·546	·416	·275	·909	·906	·877	·818	·741	·643
III	·880	·817	·728	·618	·492	·356	·215	·917	·933	·916	·877	·816	·727
November I	·871	·794	·694	·575	·440	·301	·161	·924	·953	·955	·931	·888	·811
II	·862	·772	·663	·535	·396	·253	·115	·928	·970	·989	·976	·951	·893
III	·854	·755	·638	·505	·362	·219	·082	·930	·983	1·011	1·011	·996	·959
December I	·848	·742	·619	·482	·339	·194	·062	·932	·992	1·027	1·039	1·027	1·009
II	·844	·734	·608	·469	·324	·180	·051	·932	·993	1·037	1·055	1·047	1·039
III	·845	·735	·607	·443	·324	·173	·052	·932	·999	1·039	1·056	1·050	1·042

TABLE C.—0·29 Cos φ + 0·52 n/N FOR VALUES OF LATITUDE φ FROM 0–10° (UPPER FIGURES)
TABLE E.—0·10 + 0·90 n/N (LOWER FIGURES)

n/N	0	·01	·02	·03	·04	·05	·06	·07	·08	·09
0	·29 ·10	·30 ·11	·30 ·12	·31 ·13	·31 ·14	·32 ·14	·32 ·15	·33 ·16	·33 ·17	·34 ·18
·10	·34 ·19	·35 ·20	·35 ·21	·36 ·22	·36 ·23	·37 ·24	·37 ·24	·38 ·25	·38 ·26	·38 ·27
·20	·39 ·28	·40 ·29	·40 ·30	·41 ·31	·41 ·32	·42 ·32	·43 ·33	·43 ·34	·44 ·35	·44 ·36
·30	·45 ·37	·45 ·38	·46 ·39	·46 ·40	·47 ·41	·47 ·42	·48 ·42	·48 ·43	·49 ·44	·49 ·45
·40	·50 ·46	·50 ·47	·51 ·48	·51 ·49	·52 ·50	·52 ·50	·53 ·51	·53 ·52	·54 ·53	·54 ·54
·50	·55 ·55	·56 ·56	·56 ·57	·57 ·58	·57 ·59	·58 ·60	·58 ·60	·58 ·61	·59 ·62	·60 ·63
·60	·60 ·64	·61 ·65	·61 ·66	·62 ·67	·62 ·68	·63 ·68	·63 ·69	·64 ·70	·64 ·71	·65 ·72
·70	·65 ·73	·66 ·74	·66 ·75	·67 ·76	·67 ·77	·68 ·78	·69 ·78	·69 ·79	·70 ·80	·70 ·81
·80	·71 ·82	·71 ·83	·72 ·84	·72 ·85	·73 ·86	·73 ·86	·74 ·87	·74 ·88	·75 ·89	·75 ·90
·90	·76 ·91	·76 ·92	·77 ·93	·77 ·94	·78 ·95	·78 ·96	·79 ·96	·79 ·97	·80 ·98	·80 ·99

TABLE C1.—0·29 Cos φ + 0·52 n/N FOR VALUES OF LATITUDE φ FROM 11–60°

LATITUDE	n/N	0	·1	·2	·3	·4	·5	·6	·7	·8	·9
	11–18°	0·28	0·33	0·38	0·44	0·49	0·54	0·59	0·64	0·70	0·75
	19–23°	0·27	0·32	0·37	0·43	0·48	0·53	0·58	0·63	0·69	0·74
	24–27°	0·26	0·31	0·36	0·42	0·47	0·52	0·57	0·62	0·68	0·73
	28–31°	0·25	0·30	0·35	0·41	0·46	0·51	0·56	0·61	0·67	0·72
	32–35°	0·24	0·29	0·34	0·40	0·45	0·50	0·55	0·60	0·66	0·71
	36–38°	0·23	0·28	0·33	0·39	0·44	0·49	0·54	0·59	0·65	0·70
	39–41°	0·22	0·27	0·32	0·38	0·43	0·48	0·53	0·58	0·64	0·69
	42–44°	0·21	0·26	0·31	0·37	0·42	0·47	0·52	0·57	0·63	0·68
	45–47°	0·20	0·25	0·30	0·36	0·41	0·46	0·51	0·56	0·62	0·67
	48–50°	0·19	0·24	0·29	0·35	0·40	0·45	0·50	0·55	0·61	0·66
	51–53°	0·18	0·23	0·28	0·34	0·39	0·44	0·49	0·54	0·60	0·65
	54–56°	0·17	0·22	0·27	0·33	0·38	0·43	0·48	0·53	0·59	0·64
	57–58°	0·16	0·21	0·26	0·32	0·37	0·42	0·47	0·52	0·58	0·63
	59–60°	0·15	0·20	0·25	0·31	0·36	0·41	0·46	0·51	0·57	0·62

Mean difference for 0·01 increase in n/N is 0·0052.

TABLE F.—VALUES OF $\sigma T_a^4 (0{\cdot}56 - 0{\cdot}08\sqrt{e^1})$ FOR e^1 IN MILLIBARS (UPPER FIGURES)

TABLE H.—VALUES OF $(e - e^1) \times 1/10$ (LOWER FIGURES)

Mean Dew Point °C	Mean Air Temperature °C.																															
	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
5	3·90	3·96	4·02	4·07	4·13	4·19	4·25	4·31	4·37	4·43	4·50	4·56	4·62	4·69	4·75	4·82	4·88	4·95	5·02	5·08	5·15	5·22	5·29	5·36	5·44	5·51	5·58	5·65	5·73	5·80	5·88
	0	0·06	0·13	0·20	0·27	0·35	0·44	0·53	0·63	0·73	0·83	0·95	1·07	1·19	1·33	1·47	1·61	1·77	1·94	2·11	2·29	2·49	2·69	2·91	3·13	3·37	3·62	3·88	4·16	4·45	4·75
6		3·85	3·91	3·96	4·02	4·08	4·13	4·19	4·25	4·31	4·37	4·43	4·49	4·56	4·62	4·68	4·75	4·81	4·88	4·94	5·01	5·08	5·15	5·21	5·28	5·35	5·43	5·50	5·57	5·64	5·72
		0	0·07	0·14	0·21	0·29	0·38	0·47	0·56	0·66	0·77	0·88	1·00	1·13	1·26	1·40	1·55	1·71	1·87	2·05	2·23	2·43	2·63	2·85	3·07	3·31	3·56	3·82	4·10	4·39	4·69
7			3·81	3·86	3·92	3·97	4·03	4·09	4·14	4·20	4·26	4·32	4·38	4·44	4·50	4·56	4·63	4·69	4·75	4·82	4·88	4·95	5·02	5·08	5·15	5·22	5·29	5·36	5·43	5·50	5·57
			0	0·07	0·15	0·23	0·31	0·40	0·50	0·60	0·70	0·82	0·93	1·06	1·19	1·34	1·49	1·64	1·81	1·98	2·17	2·36	2·56	2·78	3·00	3·24	3·49	3·75	4·03	4·32	4·62
8				3·75	3·80	3·86	3·91	3·97	4·02	4·08	4·14	4·19	4·25	4·31	4·37	4·43	4·49	4·55	4·61	4·68	4·74	4·80	4·87	4·93	5·00	5·07	5·13	5·20	5·27	5·34	5·41
				0	0·07	0·15	0·24	0·33	0·43	0·53	0·63	0·75	0·87	0·99	1·12	1·27	1·41	1·57	1·74	1·91	2·09	2·29	2·49	2·71	2·93	3·17	3·42	3·68	3·96	4·25	4·55
9					3·69	3·74	3·79	3·85	3·90	3·95	4·01	4·07	4·12	4·18	4·24	4·30	4·35	4·41	4·47	4·54	4·60	4·66	4·72	4·78	4·85	4·91	4·98	5·04	5·11	5·18	5·24
					0	0·08	0·17	0·25	0·35	0·45	0·56	0·67	0·79	0·92	1·05	1·19	1·34	1·50	1·66	1·84	2·02	2·21	2·42	2·63	2·86	3·10	3·35	3·61	3·88	4·17	4·48
10						3·62	3·67	3·73	3·78	3·83	3·89	3·94	3·99	4·05	4·11	4·16	4·22	4·28	4·34	4·39	4·45	4·51	4·57	4·64	4·70	4·76	4·82	4·89	4·95	5·02	5·08
						0	0·09	0·17	0·27	0·37	0·48	0·59	0·71	0·84	0·97	1·11	1·26	1·42	1·58	1·76	1·94	2·13	2·34	2·55	2·78	3·02	3·27	3·53	3·80	4·09	4·40
11							3·54	3·59	3·64	3·69	3·75	3·80	3·85	3·91	3·96	4·01	4·07	4·12	4·18	4·24	4·29	4·35	4·41	4·47	4·53	4·59	4·65	4·71	4·77	4·84	4·90
							0	0·09	0·19	0·29	0·39	0·51	0·63	0·75	0·89	1·03	1·17	1·33	1·50	1·67	1·85	2·05	2·25	2·47	2·69	2·93	3·18	3·44	3·72	4·01	4·31
12								3·46	3·51	3·56	3·61	3·66	3·71	3·76	3·81	3·86	3·92	3·97	4·03	4·08	4·14	4·19	4·25	4·30	4·36	4·42	4·48	4·54	4·60	4·66	4·72
								0	0·09	0·20	0·30	0·42	0·53	0·66	0·79	0·94	1·08	1·24	1·41	1·58	1·77	1·96	2·16	2·38	2·60	2·84	3·09	3·35	3·63	3·92	4·22
13									3·37	3·42	3·47	3·52	3·57	3·62	3·67	3·72	3·77	3·82	3·87	3·92	3·98	4·03	4·08	4·14	4·19	4·25	4·31	4·36	4·42	4·48	4·54
									0	0·10	0·21	0·32	0·44	0·57	0·70	0·84	0·99	1·15	1·31	1·49	1·67	1·86	2·07	2·28	2·51	2·75	3·00	3·26	3·53	3·82	4·13
14										3·28	3·33	3·38	3·42	3·47	3·52	3·57	3·62	3·67	3·72	3·77	3·82	3·87	3·92	3·97	4·03	4·08	4·13	4·19	4·24	4·30	4·36
										0	0·11	0·22	0·34	0·47	0·60	0·74	0·89	1·05	1·21	1·39	1·57	1·76	1·97	2·18	2·41	2·65	2·89	3·16	3·43	3·72	4·03
15											3·19	3·24	3·28	3·33	3·37	3·42	3·47	3·51	3·56	3·61	3·66	3·71	3·76	3·81	3·86	3·91	3·96	4·01	4·07	4·12	4·17
											0	0·11	0·23	0·36	0·49	0·63	0·78	0·94	1·10	1·28	1·46	1·66	1·86	2·07	2·30	2·54	2·79	3·05	3·33	3·62	3·92
16												3·08	3·12	3·17	3·21	3·26	3·30	3·35	3·39	3·44	3·48	3·53	3·58	3·63	3·67	3·72	3·77	3·82	3·87	3·92	3·97
												0	0·12	0·25	0·38	0·52	0·67	0·83	0·99	1·17	1·35	1·54	1·75	1·96	2·19	2·43	2·67	2·94	3·21	3·50	3·81
17													2·97	3·01	3·05	3·09	3·13	3·18	3·22	3·26	3·31	3·35	3·40	3·44	3·49	3·54	3·58	3·63	3·68	3·73	3·77
													0	0·13	0·26	0·40	0·55	0·71	0·87	1·05	1·23	1·42	1·63	1·84	2·07	2·31	2·56	2·82	3·09	3·38	3·69
18														2·85	2·89	2·93	2·97	3·01	3·05	3·09	3·13	3·18	3·22	3·26	3·30	3·35	3·39	3·44	3·48	3·53	3·58
														0	0·13	0·27	0·42	0·58	0·75	0·92	1·10	1·30	1·50	1·72	1·94	2·18	2·43	2·69	2·97	3·26	3·56
19															2·71	2·75	2·79	2·83	2·86	2·90	2·94	2·98	3·02	3·06	3·10	3·14	3·19	3·23	3·27	3·31	3·36
															0	0·14	0·29	0·45	0·61	0·79	0·97	1·16	1·37	1·58	1·81	2·05	2·30	2·56	2·83	3·12	3·43
20																2·57	2·61	2·64	2·68	2·71	2·75	2·79	2·83	2·86	2·90	2·94	2·98	3·02	3·06	3·10	3·14
																0	0·15	0·31	0·47	0·65	0·83	1·02	1·23	1·44	1·67	1·91	2·15	2·42	2·69	2·98	3·29
21																	2·43	2·46	2·49	2·53	2·56	2·60	2·63	2·67	2·70	2·74	2·77	2·81	2·85	2·88	2·92
																	0	0·16	0·32	0·50	0·68	0·87	1·08	1·29	1·52	1·76	2·01	2·27	2·55	2·83	3·14
22																		2·28	2·31	2·34	2·37	2·40	2·43	2·47	2·50	2·53	2·57	2·60	2·63	2·67	2·70
																		0	0·17	0·34	0·52	0·72	0·92	1·14	1·36	1·60	1·85	2·11	2·39	2·68	2·98
23																			2·11	2·13	2·16	2·19	2·22	2·25	2·28	2·31	2·34	2·37	2·40	2·44	2·47
																			0	0·17	0·36	0·55	0·76	0·97	1·20	1·43	1·68	1·95	2·22	2·51	2·81
24																				1·93	1·96	1·98	2·01	2·04	2·06	2·09	2·12	2·15	2·17	2·20	2·23
																				0	0·18	0·38	0·58	0·80	1·02	1·26	1·51	1·77	2·05	2·34	2·64
25																					1·75	1·77	1·80	1·82	1·85	1·87	1·89	1·92	1·95	1·97	2·00
																					0	0·19	0·40	0·61	0·84	1·08	1·33	1·59	1·86	2·15	2·46
26																						1·55	1·57	1·59	1·61	1·63	1·65	1·68	1·70	1·72	1·74
																						0	0·20	0·42	0·65	0·88	1·13	1·39	1·67	1·96	2·26
27																							1·34	1·36	1·38	1·39	1·41	1·43	1·45	1·47	1·49
																							0	0·21	0·44	0·68	0·93	1·19	1·47	1·75	2·06
28																								1·13	1·14	1·16	1·17	1·19	1·20	1·22	1·23
																								0	0·23	0·46	0·71	0·97	1·25	1·54	1·84
29																									0·91	0·92	0·93	0·94	0·95	0·97	0·98
																									0	0·24	0·49	0·75	1·03	1·31	1·62
30																										0·66	0·67	0·68	0·69	0·70	0·71
																										0	0·25	0·51	0·79	1·08	1·38

TABLE OF MAXIMUM POSSIBLE HOURS OF SUNSHINE, N. (FOR LATITUDE φ FROM 60° N. TO 60° S.)

10-DAY PERIODS	0°	10° N.	20° N.	30° N.	40° N.	50° N.	60° N.	10° S.	20° S.	30° S.	40° S.	50° S.	60° S.
January I	12·1	11·6	11·0	10·3	9·4	8·2	6·2	12·7	13·3	14·0	14·9	16·2	18·6
II	12·1	11·6	11·0	10·4	9·6	8·5	6·7	12·7	13·2	13·9	14·8	16·0	18·1
III	12·1	11·7	11·2	10·6	9·9	9·0	7·4	12·6	13·1	13·7	14·5	15·6	17·4
February I	12·1	11·7	11·3	10·9	10·3	9·5	8·3	12·5	13·0	13·5	14·2	15·1	16·6
II	12·1	11·8	11·5	11·1	10·7	10·4	9·1	12·5	12·8	13·3	13·8	14·6	15·8
III	12·1	11·9	11·6	11·4	11·0	10·6	9·9	12·4	12·6	13·0	13·4	13·9	14·8
March I	12·1	12·0	11·8	11·6	11·4	11·2	10·8	12·3	12·5	12·7	12·9	13·3	13·9
II	12·1	12·1	12·0	11·9	11·9	11·8	11·6	12·2	12·3	12·4	12·5	12·7	13·0
III	12·1	12·2	12·2	12·3	12·3	12·4	12·6	12·1	12·1	12·1	12·1	12·1	12·1
April I	12·1	12·3	12·4	12·6	12·8	13·1	13·6	12·0	11·9	11·8	11·6	11·5	11·2
II	12·1	12·3	12·6	12·9	13·2	13·7	14·5	11·9	11·7	11·5	11·2	10·9	10·3
III	12·1	12·4	12·8	13·2	13·6	14·3	15·4	11·8	11·5	11·2	10·8	10·2	9·4
May I	12·1	12·5	12·9	13·4	14·0	14·9	16·2	11·8	11·4	10·9	10·4	9·6	8·5
II	12·1	12·6	13·1	13·6	14·3	15·4	17·0	11·7	11·2	10·7	10·0	9·1	7·7
III	12·1	12·6	13·2	13·8	14·7	15·8	17·8	11·6	11·1	10·5	9·7	8·7	6·9
June I	12·1	12·7	13·3	14·0	14·9	16·2	18·4	11·6	11·0	10·3	9·5	8·3	6·3
II	12·1	12·7	13·3	14·1	15·0	16·3	18·8	11·5	10·9	10·2	9·4	8·1	6·0
III	12·1	12·7	13·3	14·1	15·0	16·4	18·8	11·5	10·9	10·2	9·3	8·1	5·9
July I	12·1	12·7	13·3	14·0	14·9	16·2	18·4	11·6	11·0	10·3	9·4	8·2	6·2
II	12·1	12·7	13·2	13·9	14·8	16·0	18·1	11·6	11·0	10·4	9·6	8·5	6·7
III	12·1	12·6	13·1	13·7	14·5	15·6	17·4	11·7	11·2	10·6	9·9	9·0	7·4
August I	12·1	12·5	13·0	13·5	14·2	15·1	16·6	11·7	11·3	10·9	10·3	9·5	8·3
II	12·1	12·5	12·8	13·3	13·8	14·6	15·8	11·8	11·5	11·1	10·7	10·1	9·1
III	12·1	12·4	12·6	13·0	13·4	13·9	14·8	11·9	11·6	11·4	11·0	10·6	9·9
September I	12·1	12·3	12·5	12·7	12·9	13·3	13·9	12·0	11·8	11·6	11·4	11·2	10·8
II	12·1	12·2	12·3	12·4	12·5	12·7	13·0	12·1	12·0	11·9	11·9	11·8	11·6
III	12·1	12·1	12·1	12·1	12·1	12·1	12·1	12·2	12·2	12·3	12·3	12·4	12·6
October I	12·1	12·0	11·9	11·8	11·6	11·5	11·2	12·3	12·4	12·6	12·8	13·1	13·6
II	12·1	11·9	11·7	11·5	11·2	10·9	10·3	12·3	12·6	12·9	13·2	13·7	14·5
III	12·1	11·8	11·5	11·2	10·8	10·2	9·4	12·4	12·8	13·2	13·6	14·3	15·4
November I	12·1	11·8	11·4	10·9	10·4	9·6	8·5	12·5	12·9	13·4	14·0	14·9	16·2
II	12·1	11·7	11·2	10·7	10·0	9·1	7·7	12·6	13·1	13·6	14·3	15·4	17·0
III	12·1	11·6	11·1	10·5	9·7	8·7	6·9	12·6	13·2	13·8	14·7	15·8	17·8
December I	12·1	11·6	11·0	10·3	9·5	8·3	6·3	12·7	13·3	14·0	14·9	16·2	18·4
II	12·1	11·5	10·9	10·2	9·4	8·1	6·0	12·7	13·3	14·1	15·0	16·3	18·8
III	12·1	11·5	10·9	10·2	9·3	8·1	5·9	12·7	13·3	14·1	15·0	16·4	18·8