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IRRIGATION SCHEDULING PROGRAM FOR SUGARCANE

by

Terence L. Pearse

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Soil Science and Biometeorology

(Irrigation Science)

UTAH STATE UNIVERSITY
Logan, Utah

1976

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Terence L. Pearse

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ABSTRACT

Irrigation Scheduling Program for Sugarcane

by

Terence L. Pearse, Master of Science

Utah State University, 1976

Major Professor: Dr. R. J. Hanks
Department: Soil Science and Biometeorology

An estimate of potential evapotranspiration is acquired to implement an irrigation scheduling program. Four equations, which estimate potential evapotranspiration (evaporation) were evaluated for prediction of Class "A" Pan evaporation. The equations used were Penman's combination equation, the Jensen-Haise temperature and radiation equation, and two of the Christiansen-Hargreaves polynomial regression type equations. Measured and calculated radiation was used together with two values of albedo. Four years of daily climate data from Rhodesia was evaluated by general linear regression methods.

Despite the significant variations between the four annual regression lines of each equation, the use of confidence intervals indicate that the Penman and Christiansen-Hargreaves equations adequately predict Class "A" pan evaporation for irrigation control purposes.

Using Class "A" pan evaporation as the measure of potential evapotranspiration for sugarcane, a computerized irrigation scheduling model was developed.

Controlled plant moisture stress was incorporated in the program with an irrigation coefficient related to the limiting effects of low

soil moisture on plant transpiration. Five soil moisture regimes and two levels of irrigation were studied.

Within the limits of the defined soil moisture assumptions, the program exhibited considerable flexibility in computation and the control of desired plant moisture stress.

(152 pages)

INTRODUCTION

In the semi-arid and subtropical zones of the world where intensive irrigation is undertaken, the situation frequently exists where, although irrigable land is not limited, water for irrigation is.

Generally the in field management of specific crop water requirements in respect to climate, soil, and plant interactions is cumbersome and ineffective except in a rudimentary way. For example, little importance may be placed on the stage of crop growth, and scheduling may be determined by some arbitrary time factor which does not take into account available soil water or the amount of irrigation applied.

There is a need to determine the optimum crop water requirements and the means whereby effective irrigation scheduling can optimize water use and lead to a greater acreage under irrigation.

Investigations by Chang (1961) and Thompson et al. (1963) on the water requirements of sugar cane have suggested the use of evapotranspiration/pan evaporation ratios as a basis for estimating potential evapotranspiration for irrigation control. Campbell (1967, p. 653) reviewed the irrigation requirements of sugar cane and determined that

> In the tropics, the ET/E_{pan} ratio is potentially a useful method for estimating potential evapotranspiration for various stages of canopy development. Data indicate that the ratio changes from $ET/E_{pan} = 0.4$ for bare soil to about $ET/E_{pan} = 1.0$ for full canopy.

In South Africa, Thompson and Boyce (1972) investigated Penman's equation and three modifications of it to investigate how well the actual ET of sugarcane could be estimated. Only the unmodified Penman equation (coastal zone area) closely approximated measured

evapotranspiration values and they concluded that this apparent accuracy was largely fortuitous. In conclusion, they advise practicing agriculturists to use the proven empirical relationship between evapotranspiration and Class "A" pan evaporation.

This experience in Southern Africa leads to the current assumption that the Class "A" pan is the optimum means of estimating evapotranspiration for the crop. This relationship between sugarcane evapotranspiration and pan evaporation has been developed for the Rhodesian sugarcane industry (RSAES, 1974).

With a reliable measure of evapotranspiration it is possible, with an accurate understanding of the crop and soil characteristics, to develop an irrigation schedule to optimize water use and maximize crop yields (Haise, Hagan, and Edminster, 1967).

Objective

The objectives of this study are:

1. To compare Class "A" pan evaporation with estimates of potential evaporation determined by the following equations for the sugarcane growing area of the Rhodesian Lowveld:

    a. Penman's combination method.

    b. Jensen-Haise temperature and radiation method.

    c. The Christiansen-Hargreaves polynomial regression equations.

2. Develop an effective method of control for scheduling the irrigation of sugarcane to facilitate optimum water use.

REVIEW OF LITERATURE

Evaporation

Three physical requirements are needed for water to be evaporated into the air from the plant, soil, and/or water surface at a potential rate. These are, as defined by Rose (1966),

1. A supply of heat (energy) to provide the large latent heat of vaporization component.

2. That the vapor pressure in the overlying air must be maintained at less than the evaporation surface.

3. There should be a continual supply of free water for evaporation.

Free water surface. Evaporation from a free water surface has been measured by many kinds of evaporimeters including the Class "A" evaporation pan. These measurements are used, with suitable coefficients, to estimate actual evaporation from lakes and reservoirs, as well as evapotranspiration from crops (ASA, 1967).

Bare soil. The evaporation rate from wet bare soil is about the same as from a free water surface. However, if the wet soil surface is not replenished by irrigation or rainfall, the evaporation from the soil rapidly approaches zero within a few days. The primary reason being that the soil is unable to maintain constant transmission of water to the surface at the rate of evaporative demand (Hillel, 1971; Taylor and Ashcroft, 1972).

Transpiration

Transpiration is the moisture loss from the soil to the atmosphere through the plant system. The proportion of water use by transpiration is a function of the leaf cover, being small in the emerging crop and increasing as the leaf area increases. It is generally difficult to separate soil evaporation and transpiration processes so they are usually treated as a single process called evapotranspiration.

Evapotranspiration

Evapotranspiration rarely remains constant because it is influenced by soil-plant and atmospheric factors, none of which are static factors. For convenience, evapotranspiration has been defined in terms of potential and actual.

Potential evapotranspiration. Taylor and Ashcroft (1972, p. 46) defined potential evapotranspiration as

> ... the amount of water that could be evapotranspired in a unit time by a short green crop of uniform height completely shading the ground and never lacking for water.

Actual evapotranspiration. Hillel (1971), in a review of the soil-plant-atmosphere indicates that potential evapotranspiration rarely exists due to a number of soil and plant factors. In practice, the potential evapotranspiration estimates are converted to actual evapotranspiration by multiplying potential evapotranspiration by a crop-soil factor.

Measurement of potential evapotranspiration

During the past 25 years, numerous equations and procedures have been developed to predict evapotranspiration. The list of formulas developed (Doorenbos and Pruitt, 1975; Jensen, 1973) is large, but generally all are based on any one or more of the five rational methods (Tanner, 1967) which are:

1. Hydrologic or water balance approaches, which includes lysimetery and soil moisture depletion sampling.

2. Eddy correlation methods which in principle combine the interaction of specific humidity and surface wind turbulence and mixing in the laminar boundary just above the evaporating surface. (See also Rose, 1966.)

3. The energy balance approach, wherein incoming radiation is balanced between latent heat of vaporization, soil heat flow, and sensible heat flow.

4. The aerodynamic or profile method where the vapor mass flux is the product of the turbulent diffusivity (or transfer coefficient) and the vapor pressure gradient.

5. The combination approach, which is based on the energy balance and aerodynamic transport principles. The energy components are measured directly and an aerodynamic term is used to evaluate sensible heat exchange to sustain evaporation from the surface.

These methods all have a rational basis but limits on their applicability depend on a number of factors and assumptions, notably,

a. Availability of climatic data.

b. Complexity and cost of equipment and sensing devices for data collection.

c. Local practical, technical, social, and economic considerations.

d. Inaccuracies in the basic equations.

The difficulties which may arise from the above factors have led to the development of empirical formulas which are based on multiple correlation techniques. These methods have been effectively demonstrated by Blaney and Criddle, Christiansen and Hargreaves, Thornthwaite and Jensen, and Haise, among many others (Jensen, 1973; Doorenbos and Pruitt, 1975). These empirical equations use a range of climatic variables which can be reasonably easily obtained from regular weather stations to develop empirical evapotranspiration indices which will relate to potential evapotranspiration.

Jensen (1973), in a detailed study of many formulas, determined that a wide range of variation exists between values of calculated potential evapotranspiration and measured evapotranspiration over a range of climatic sites. The combination equations were consistently the best climatic method of estimating potential evapotranspiration with the others showing good to moderate consistency.

Class "A" pan evaporation

Details of construction and operation of the Standard U. S. Weather Bureau Class "A" Pan for use in Rhodesia is given by Metelerkamp (1968).

Although potential evapotranspiration and pan evaporation are often considered synonymous, the former has distinct crop and soil characteristics which cause differences in magnitude to occur, particularly due to the leaf canopy cover and age of the crop.

Tanner (1967) stated that there is a high correlation between potential evapotranspiration and pan evaporation when soil water is not limiting. Parmele and McGuinnes (1974), in comparisons between actual evapotranspiration and various methods of potential evapotranspiration obtained consistently high correlations between measured Class "A" pan evaporation and actual evapotranspiration.

Tanner (1967), Hanks (1970), Christiansen (1972), and Jensen (1973) all emphasize the importance of site selection in the use of pan evaporation. Pruitt (1966) found that evaporation from a pan surrounded by dry soil was 20 percent higher than one surrounded by well-watered short grass. Jensen (1973) presents a table of coefficients for relating pan evaporation to evapotranspiration from a well-watered grass turf.

Christiansen (1972) suggests that if pan evaporation is not readily available, a number of equations can be used to estimate pan evaporation.

The growth of sugar cane

Mangelsdorff, cited in Humbert (1968), characterizes the ideal climate for the production of sugar from sugarcane as:

a. A long, warm summer growing season with adequate rainfall.

b. A fairly dry, sunny, and cool but frostfree ripening and harvest season.

Low seasonal mean temperatures and sunlight tend to extend the period of growth. In Hawaii sugarcane is harvested every 23-24 months; in South Africa, depending on climatic zones, between 12 and 20 months; and in Rhodesia, every 12 to 14 months.

The crop cycle of sugarcane can be conveniently divided into irrigation periods. In Southern Africa where the crop cycle under irrigation is between 12 and 14 months, Gosnell (1970) and Thompson and Boyce (1968) divide the period of growth into:

1. Precanopy period which extends from harvest (planting) to the time when full canopy is reached.

2. The full canopy period.

3. The ripening period which is essentially a period prior to harvest with reduced moisture availability.

Campbell (1967), for areas of extended growth periods such as in Hawaii, suggests a fourth period during which early senescence occurs before the ripening (drying off) period.

Evapotranspiration of sugarcane

Numerous studies have been undertaken to determine the actual evapotranspiration of sugarcane. Although a tropical crop, sugarcane is grown in areas varying from arid to humid regions where rainfall greatly exceeds the evapotranspiration rate of the crop.

The water requirements for sugarcane (evapotranspiration) have been measured by means of lysimeters in a number of countries, in particular Hawaii, Australia, and South Africa (Campbell, 1967; Humbert, 1968).

Campbell (1967), Humbert (1968), Thompson et al. (1963), Thompson and Boyce (1971), and Gosnell (1970) in their reviews and studies of

evapotranspiration in sugarcane have determined that the ratio of lysimeter to pan evaporation increased from 0.4 when growth begins to values varying between 1.0 and 1.1 at full canopy.

Yields of sugarcane related to water use

Chang (1961) and Thompson et al. (1963) determined a relationship between water use and crop production. Chang, in Hawaii, determined this relationship to be about 12 tons of cane per hectare per 100 mm of water use. Thompson et al. (1963) and Thompson and Boyce (1971), in South Africa, determined this ratio to be about 11 tons cane per hectare per 100 mm of water use. A summary of water use investigations at the Rhodesia Sugar Association Experiment Station (1974) supports these findings with a value of about 11 tons per hectare per 100 mm of water.

Effects of soil moisture on plant water uptake

Stanhill and Vaadia (1967) review the difficulty in providing a general relationship between plant and soil in respect to soil moisture availability. The soil-plant-atmosphere continuum is in a constant state of flux, with the ability of the plant to transpire at the potential levels limited by evaporative demand in the atmosphere or limited soil water availability in the soil.

Hillel (1971) reviewed some of the newer theories and outlined the three classical concepts regarding the availability of soil water to plants. Figure 1 illustrates the three concepts where,

a. Defines equal availability from field capacity to wilting point.

b. Equal availability from field capacity to a 'critical point' of moisture content beyond which availability decreases as some function of lowering soil water content.

c. A linear decrease in availability from field capacity to wilting point.

Haise and Hagan (1967) discuss the generalized relationship between volumetric water content and soil water potential as affected by soil texture. Figure 2, as cited by the authors, is reproduced to illustrate this concept. It shows water retention curves for several soils plotted in terms of percent available water removed.

It has been determined that plant response to irrigation is better correlated with soil water potential or suction when the soils have not been calibrated for soil water content (Hagan and Haise, 1967).

The 'critical point' as indicated by line (b) in Figure 2 can be evaluated in terms of soil suction. Hagan and Haise (1967) list the maximum values of soil suction required to obtain maximum yields for different crops.

The concept of a 'critical point,' where soil water limits evapotranspiration, was adopted in this study with the 'critical point' being evaluated on the basis of maximum soil suction depletion value for optimum sugarcane growth which, in turn, was approximated by Figure 2 to percent depletion of soil moisture by textural class.

Soil moisture relationships of sugarcane

Sugarcane is a fibrous rooted crop, the roots of which are most active in the first 2 or 3 feet of the soil profile. This general

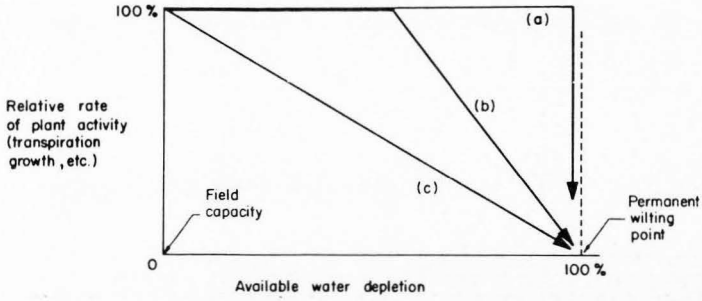

Figure 1. Three hypotheses regarding the availability of soil water to plants (after Hillel, 1971).

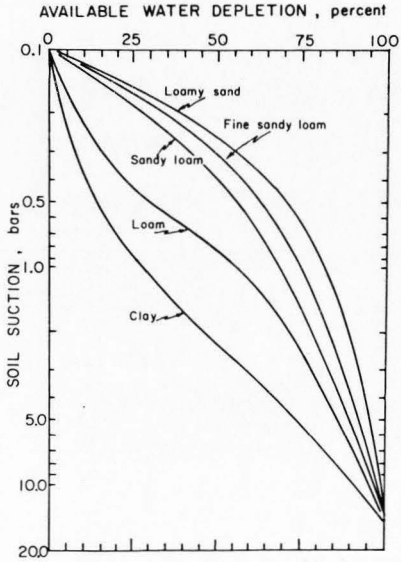

Figure 2. Water retention curves for several soils plotted in terms of percent available water removed (after Haise and Hagan, 1967).

pattern will vary depending upon the physical condition of the soil.

When depth is not limiting, the texture of the soil effects the moisture extraction pattern. Thompson et al. (1967) indicate that sufficient amounts of moisture will be extracted to depths of 6 feet in sands but will rarely exceed 3 feet in clays. They conclude that the effective mean rooting depth is about 3 feet with maximum with maximum utilization of water occurring only in the top 1 foot.

Robinson (1963) reported that the rate of elongation in the sugarcane plant declines as the matric potential in the soil approaches -2 bars. However, Haise and Hagan (1967) listed a value of -0.25 to -0.30 bar matric potential for optimum sugar yield. A value of -1.0 bar was adopted for this study.

Irrigation management factors

"When water is a principle limiting factor, sugar yield produced per m^3 of water applied may be of as great importance as sugar yield per hectare" (Gosnell and Lonsdale, 1974, p. 9).

During the ripening period prior to harvest (drying off) it is desirable to increase the moisture stress. Thompson and Boyce (1968) indicate an improvement in juice purity and sucrose content with this practice. The Rhodesia Sugar Association Experiment Station (1974) indicates that maximum yield of sucrose per unit area and also per unit amount of irrigation water applied occurs when drying off prior to harvest is implemented.

Data from irrigation/lysimeter trials in Rhodesia (RSAES, 1974) has indicated that although evapotranspiration/pan evaporation ratios

of over 1.0 were obtained, it appears that a factor of about 0.85 was optimal during the period of peak water use (full canopy), followed by drying off at a ratio fo 0.60. A more detailed development of this aspect is covered later.

Lodging of sugarcane may influence evapotranspiration by as much as 30 percent (Thompson and Boyce, 1971). Although no data is available, it is recommended that the full crop factor of 0.85 be lowered to 0.60 until growth in the lodged area returns to normal upright habit (RSAES, 1974).

Scheduling of irrigation

Increased productivity and efficiency of irrigated agriculture will be dependent upon the accurate determination of when and how much water to apply to the crop.

Jensen (1972) lists the following points as limitations in the improvement of irrigation techniques:

a. The lack of decision-making data.

b. Too few economic incentives to improve irrigation efficiency.

c. Increasing labor costs and hardware which are frequently not offset by significantly improved irrigation efficiencies.

In the past various soil, plant, and evaporative techniques have been used as criteria for establishing irrigation schedules for a given crop and climatic area (Haise and Hagan, 1967). These techniques, despite the accuracy of instrumentation, such as the neutron probe, tensiometers, or sampling, have, in the past, been time consuming, expensive, and in many instances, labor consuming.

The development of criteria which will aid in defining the exact time and amount of irrigation is dependent upon a number of interrelated crop/soil/water factors. Jensen (1969) defines these as follows:

a. Daily potential evapotranspiration, which is determined by any of a large number of equations or instruments (Tanner, 1967).

b. Crop coefficients must be known for all stages of crop growth and must be related to a chosen measure of potential evapotranspiration.

c. Soil moisture which is a function of depth, texture, and rooting depth of the crop.

d. Optimum soil moisture depletion which should reflect the available soil moisture characteristics and the crop tolerance to varying degrees of soil moisture stress.

e. Irrigation timing and amount which is dependent largely upon system design.

The advent of the computer has enlarged the scope of irrigation scheduling (Jensen, 1969; Franzoy and Tankersley, 1970; Jensen, Ross, and Franzoy, 1970; Buras, Nir, and Alpervits, 1973). The approach is a water accounting procedure wherein estimates of daily evaporation and transpiration for a crop, when combined with data of allowable soil moisture depletion for the crop on a given soil, will lead to an estimate of when the next irrigation should occur.

Jensen (1972) and the Agricultural Research Service (1975) indicate that until the early 1960's little change had occurred in irrigation scheduling during the previous 25 years. Since the late 1960's when the formation of Irrigation Scheduling Services (ISS) in Southern Idaho

Arizona, and Nebraska started, there has been a rapid increase in commercial and government related agencies. ARS (1975) cites that of the approximately 35 ISS operations currently in existence almost 30 have had less than 5 years experience. This reflects the growth of the application of centralized scientific irrigation scheduling in recent years.

Costs in 1972 ranged from $4.00 to $10.00 per hectare, depending on the area and frequency of data processing (Jensen, 1972). More recent values indicate a range in cost of between $10.00 and $25.00 per hectare (ARS, 1975).

Jensen (1972) emphasizes the need for more information of site-specific factors such as:

a. Crop yields relative to crop water use.

b. Evapotranspiration as it affects water use by the crop.

c. Meteorological observations which would lead to better estimation procedures of potential evapotranspiration.

PART I

COMPARISON OF POTENTIAL EVAPOTRANSPIRATION FORMULAS WITH CLASS "A" PAN EVAPORATION

PROCEDURE

Introduction

Class "A" pan evaporation is currently used as a measure of the potential evapotranspiration of sugarcane in Rhodesia. Any alternative approach is determined by the type of climatic data available. This study investigates a selected number of equations and determines how well the estimates correlate with Class "A" pan evaporation. High correlations would imply the possible substitution of an equation using a range of climatic data in place of Class "A" pan evaporation for irrigation control.

Four formulas are to be correlated with known pan evaporation values to investigate the ability of the equations, by simple linear correlation techniques, to predict pan evaporation. These equations are:

1. Penman-Combination type
2. Jensen-Haise temperature/radiation type.
3. Two Christiansen-Hargreaves equations based on regular climatic and radiation measurements.

Penman-Combination Method

The classical formula using the combination method is the Penman equation. The theory, development and variations of the equation are well documented by Penman (1948, 1961), ASA (1967), Rose (1966), Tanner (1968), Taylor and Ashcroft (1972), Jensen (1973), and Sellars (1974).

The equation can be written in the general form as follows:

$$E_o = \frac{\Delta}{\Delta + \gamma}(R_n + G) + \frac{\Delta}{\Delta + \gamma}(f(u)(e_z^o - e_z)) \qquad [1]$$

where R_n = net radiation

G = soil heat flux

Δ = slope of the vapor pressure - temperature curve

γ = pyschrometric constant

z = measured height above the surface

$f(u)$ = wind function

e_z^o = saturated vapor pressure at average temperature

e_z = actual vapor pressure.

Energy component in Penman's equation

The energy component, largely net radiation, is subject to some variability in determination. In this study the variation is subject to the following factors which will be discussed in the section on radiation measurement:

a. Sources of radiation data.

   i. Measured with a Gunn Bellani pyranometer.

   ii. Calculated by using geographical and solar variables.

b. Short wave reflectance or albedo (α).

   i. Use of the value for short wave reflectance from open water (α = 0.05).

   ii. Use of the mean value for a vigorously growing green crop (α = 0.23).

Wind function

Jensen (1973) reviews the development of variations in the wind function (f(u)). Early calibration of data resulted in the following function for evaporation from a 63 cm diameter pan, where wind speed (u) was in miles per day:

$$f(u) = 15.36\ (1 + 0.01\ u) \qquad [1a]$$

Penman later determined that for determination of evaporation from large water surfaces the following function gave better results:

$$f(u) = 15.36\ (0.5 + 0.01\ u) \qquad [1b]$$

Penman (1963) later determined the wind function for well watered short grass to be similar to equation [1a].

Wright and Jensen (1972) determined the function for a well watered alfalfa field in the arid, advective condition of Southern Idaho to be

$$f(u) = 15.36\ (0.75 + 0.0185\ u) \qquad [1c]$$

The function used in this study, equation [1a] would appear best for comparison with Class "A" pan values obtained from a site surrounded by well-watered turfgrass. The actual wind function used, where wind speed is in kilometers per day, is,

$$f(u) = 15.36\ (1.0 + 0.0062\ u) \qquad [1d]$$

The estimates of solar radiation and the two values for albedo result in 4 forms of Penman's equation being evaluated in

this study. They are, using notation to be carried throughout the rest of the text:

a. PENMAN 1 with $\alpha = 0.23$ and calculated solar radiation.

b. PENMAN 2 with $\alpha = 0.05$ and calculated solar radiation.

c. PENMAN 3 with $\alpha = 0.23$ and measured solar radiation.

d. PENMAN 4 with $\alpha = 0.05$ and measured solar radiation.

Jensen-Haise Method

Most empirical equations using the energy concept take the format of a constant times measured solar radiation.

The value of radiation is in the form of either: R_s - the incoming solar radiation comprised of direct and scattered shortwave radiation or R_n - the net ratiation defined elsewhere in the text.

Jensen (1973) indicates that the Jensen-Haise equation developed in the early 1960's showed reliability in predicting evapotranspiration that occurred in well watered, irrigated crops located in semi-arid to arid areas.

The equation was developed from a linear relationship between crop water use, radiation and mean air temperature. From numerous field data, the following linear equation was developed:

$$E_{tp} = C_T (T - T_X) R_s \qquad [2]$$

where E_{tp} is the potential evapotranspiration for a well watered crop, C_T is the temperature coefficient, T_X is the intercept of the temperature axis, T is the daily mean temperature and R_s is incoming solar radiation.

The coefficients C_T and T_X are considered as area constants and defined as follows:

$$C_T = \frac{1}{C_1 + C_2 C_H} \qquad [2a]$$

where C_1 = 38°C - (2 x elevation in meters/305 meters)

C_H = 50 mb/(e_2 - e_1)

where e_1 = saturated vapor pressure at the mean monthly maximum temperature

e_2 = saturated vapor pressure of the mean monthly maximum temperature of the same month as the mean monthly maximum.

and C_2 = 7.6°C

$$T_x = -2.5 - 0.14\ (e_2 - e_1) - \text{elevation in meters}/550 \qquad [2b]$$

Equation [2] has demonstrated some versatility in the semi-arid areas of the western United States according to Franzoy (1969), Jensen et al. (1971) and USDA (1975). It is relatively simple and easy to evaluate and is based on the major energy input component-radiation. The equation as given is particularly accurate for areas of low relative humidity such as in the western (inland) United States, where it was developed. The adaption of this technique to differing geographical areas may require adjustment to the calculation of C_T and T_X components (Stephens, 1965).

Energy component of the Jensen-Haise equation

Two values of solar radiation will be used to evaluate this equation, and using the notation used in the remaining portion of the text, they are:

a. JENSEN 1 = Calculated R_s

b. JENSEN 2 = Measured R_s

Christiansen-Hargreaves Method

Numerous empirical equations have been developed which are generally based on multiple regression analysis of limited climatic variables which effect evaporation and evapotranspiration such as Blaney-Criddle, Thornthwaite, Makkink, Turc, and others (Jensen, 1973; Doorenbos and Pruitt, 1975). The range of climatic parameters used varies among the equations, allowing for a wide range of general applications even in areas with relatively basic climatic data records. Christiansen (1968) and Christiansen and Hargreaves (1969) developed a number of equations to predict potential evapotranspiration. One formula uses extraterrestrial radiation, R_a, as the base variable. A second formula uses solar radiation, R_s, as the base variable.

Extraterrestrial radiation

The formula relating potential evapotranspiration to extraterrestrial radiation, R_a, and climatic factors is:

$$E_{tp} = 0.324\ R_a\ C_{TT}\ C_{WT}\ C_{HT}\ C_{ST}\ C_E \qquad [3]$$

where R_a is the extraterrestrial radiation in langleys/day as an equivalent depth of evaporation. The climatic coefficients are:

$$C_{TT} = 0.463 + 0.425\ (T_C/T_{Co}) + 0.112\ (T_C/T_{Co})^2 \qquad [3a]$$

where T_C is the mean temperature in °C, and T_{Co} is 20°C.

$$C_{WT} = 0.672 + 0.406\ (W/W_o) - 0.078\ (W/W_o)^2 \qquad [3b]$$

where W is the mean wind velocity at 2 meters above ground in km/hours and W_o is 6.7 km/hour.

$$C_{HT} = 1.035 + 0.240\ (H_m/H_{mo}) - 0.275\ (H_m/H_{mo})^3 \qquad [3c]$$

where H_m is the mean relative humidity (decimal value) and H_{mo} is 0.60.

$$C_{ST} = 0.340 + 0.856\ (S/S_o) - 0.196\ (S/S_o)^2 \qquad [3d]$$

where S is the percent possible sunshine (decimal value) and S_o is 0.80.

$$C_E = 0.970 + 0.030\ (E/E_o) \qquad [3e]$$

where E is the elevation in meters and E_o is 305 meters.

In the remaining portion of this text this equation is identified by:

CHRHAR 1 = Extraterrestrial radiation equation.

Solar radiation

The formula relating potential evapotranspiration to measured incoming solar radiation, R_s can be written as:

$$E_{tp} = 0.492\ R_s\ C_{TT}\ C_{WT}\ C_{HT} \qquad [4]$$

where R_s is the measured incoming solar radiation expressed as an equivalent depth of evaporation. The equations for the climate coefficients are the same as for equation [3].

Two forms of solar radiation are used with this equation and will be identified in the remaining part of the text as:

a. CHRHAR 2 = Calculated solar radiation.

b. CHRHAR 3 = Measured solar radiation.

The equivalent depth is obtained by dividing langleys per day of radiation (R_a or R_s) by the latent heat of vaporization, L, where

$$\text{Equivalent depth in mm} = \frac{\text{Radiation value in langleys}}{L} \qquad [5]$$

At a temperature of 20°C, L has a value of 584.9 calories per gram. For other temperatures, the relation is

$$L = 595.9 - 0.55\ T_C \qquad [6]$$

where T_C is the temperature in °C.

Except when a computer is likely to be used and because of the small variation in L with temperature, the value for 20°C is generally used.

Geographic Locality

The study area is Rhodesia, which is situated in the southern portion of Africa between latitudes 15°S and 23°S. The climate ranges between tropical in the low lying areas to subtropical in the uplands.

The country has very distinct climatic seasons, highlighted by a single relatively short rainy season during the summer months from late November to the end of March. The winters are cool and dry except in the Eastern Highlands where light winter rains can occur. In the lowlying areas (200 m - 600 m), of the north, south and southeast, the absence of harsh winter conditions enables diverse cropping to be practiced throughout the year. Sugarcane is grown in the southeast area.

Climate Data

The climate data was obtained from the Rhodesia Meteorological Services Weather Station at the Buffalo Range Airport in the south-eastern area of Rhodesia. The approximate position is 21°14' S and 31°46' E with an elevation of about 420' meters above sea level.

Although not sited directly within the irrigated agricultural area, the site itself is situated within a well watered grass enclosure and is approximately 1.5 kilometers downwind of the intensively irrigated sugar cane areas.

The following climate data is measured daily at the recording station:

a. Maximum and minimum temperatures in °C

b. Wet and dry bulb temperatures in °C

c. Dew point temperature in °C

d. Relative humidity percentage

e. Wind speed at 2 meters height in miles per day

f. Sunshine percent with Campbell-Stokes recorder

g. Rainfall in mm

h. Class "A" pan evaporation in mm

i. Radiation in langleys per day.

Practical problems arising from birds, insects, and windborne debris has resulted in the Rhodesia Meteorological Service standardizing the U. S. Weather Bureau Class "A" Pan to Rhodesian conditions by placement of a 5 cm wire mesh screen across the surface. This loss of evaporation due to the screen has been compensated for by painting the inside of the evaporating pan with a matte-black finish.

Measured Solar Radiation

The solar radiation data at Buffalo Range, Rhodesia was obtained with a Gunn-Bellani pyranometer. This device has many applications in the field of biological sciences because of its ability to measure circumglobal short wave radiation which is the sum of direct and scattered solar radiation, plus radiation reflected from the surroundings (Robinson, 1966; Sellars, 1974).

The instrument is comprised of a glass or copper sphere containing alcohol which upon heating from incident radiation, vaporizes and upon cooling condenses in a graduated tube.

The response time is slow but whole day exposures yield satisfactory results (Robinson, 1966).

Due to its simplicity and low cost, it has been used by the Rhodesian Meteorological Service to measure incoming solar radiation. The elimination of the circumglobal configuration is achieved by placing the instrument in a tube at ground level so that only direct and reflected sky radiation reaches the sphere.

A further limitation of the Gunn-Bellani instrument is caused by the spherical intercepting surface. Direct solar radiation is always normal to the surface of sphere. This leads to higher values of daily radiation when compared with standard type instruments (Robinson, 1966) which measure radiation on a fixed flat surface.

The Gunn-Bellani radiation data given for Buffalo Range has not been calibrated for conversion to horizontal, flat surface, equivalent values. To overcome this requires the determination of estimated

radiation by an interrelation of a number of sunshine and radiation factors as cited by Duffie and Beckman (1974).

Calculated Extraterrestrial and Solar Radiation

The energy radiating from the sun, more commonly defined as the solar constant, I_{sc}, is expressed as energy per unit area per unit time. This value is approximately 1.86 cal per cm^2 per minute when the surface area is normal to the solar beam. The energy intercepted at the top of the atmosphere, the extraterrestrial radiation, R_a, can therefore be determined from the geometric correspondence between the beam of solar energy and the plane of the intercepting surface (Robinson, 1966; Duffie and Beckman, 1974; Sellars, 1974).

A simplification of the procedures developed in the references can be seen in Appendix A.

From daily values of extraterrestrial radiation, the solar radiation incident at the earth's surface, R_s, can be estimated from climatic and geographical variables. The estimation of solar radiation is also presented in Appendix A.

The geographical constants for Malange, Angola were used because of the similarity in general climate and proximity in latitude with Rhodesia.

Net Radiation

The energy balance portion of Penman's equation requires a knowledge of net radiation, R_n. Net radiation is a balance of the net short wave and net long wave components as shown schematicly in Figure 3.

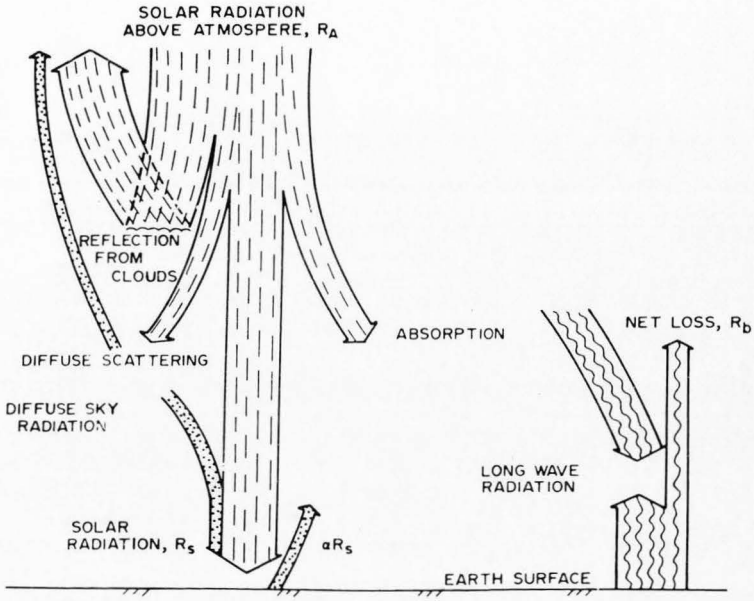

Figure 3. Schematic representation of the daytime radiation balance (after Jensen, 1973).

Net radiation, where it is not measured directly, can be determined from measured or calculated solar radiation by the following equation

$$R_n = (1 - \alpha)\ R_s - R_b \qquad [7]$$

where α is the short wave reflectance or albedo of the surface, R_s is solar radiation and R_b is the net back or outgoing longwave (thermal) radiation.

For practical purposes the net thermal radiation can be estimated if solar radiation, air temperature, and humidity are known, as follows:

$$R_b = [a' \frac{R_s}{R_{so}} + b']\ R_{bo} \qquad [8]$$

where R_{bo} is the net outgoing longwave radiation on a clear day, R_{so} is cloudless day solar radiation received at the earth's surface. The constants a' and b' are geographical constants which in this study were taken from Jensen (1973) as general arid area coefficients, where (a') equals 1.2, and (b') equals 0.2.

The net outgoing longwave radiation, R_{bo}, can be estimated as follows:

$$R_{bo} = \varepsilon' \sigma T^4 \qquad [9]$$

where T is the screen mean temperature in °K, σ is the Stephan-Boltzman constant with a value of 11.71×10^{-8} cal cm^{-2} day^{-1} $°K^{-4}$ and ε' is the net emissivity. A generalized equation for effective emittance of the atmosphere was presented by Idso and Jackson (1969) as

$$\varepsilon' = -0.02 + 0.261 \exp\ [-7.77 \times 10^{-14}\ (273 - T)^2]. \qquad [10]$$

Albedo

The determination of net radiation in Penman's equation requires knowledge of the albedo (α), or reflectivity, of the surface to incoming short wave radiation. The coefficient varies according to the type roughness and inclination of the surface. Hillel (1971) summarizes the magnitude in the order of 5-10 percent for water, 10-30 percent for a vegetated area and 15-40 percent for bare soil.

The ability of Penman's equation to predict evaporation from a Class "A" pan is dependent in part on the value of the albedo of the surface. Since the Class "A" pan values are also used as a measure of potential evapotranspiration in sugarcane, this study considers the effects of two values of albedo. Jensen (1976) suggested using 0.05 and 0.23. The value, 0.05, is an approximation of the reflectance from open water in tropical areas and 0.23 a mean approximation of reflectance from a vigorously growing full canopied green crop.

Soil heat flux

Penman's equation requires knowledge of the soil heat flux. Normally this unit is very small compared to the R_n component and is often ignored. Jensen (1973) defined an approximation for the soil heat flux, G, over extended periods of time. This approximation is based on the assumption that the average soil temperature to a depth of 2 meters changes approximately with average air temperature, and that the average volumetric heat capacity for the soil is 0.5 cal cm^{-3} $°C^{-1}$. The equation for soil heat flow is

$$G = \left(\frac{\overline{T}_{i-1} - \overline{T}_{i+1}}{\Delta t} \right) 100 \qquad [11]$$

where G is the average daily soil heat flux in cal cm^{-2} day^{-1}, $\bar{T}$ equals the mean air temperature and °C for time period i, and Δ equals the time in days between the midpoints of the two periods.

Mean temperature

The monthly mean temperature values for Buffalo Range, Rhodesia were plotted (Figure 4) and a sine wave function between minimum and maximum monthly mean values developed to approximate the expected daily seasonal values. The value of the function to predict mean daily temperatures is:

$$T = 5.3 \text{ Cos } (0.0172 \text{ D}) + 21.30 \qquad [12]$$

where T is the daily mean temperature and D is the Julian day of the year. This function was used in equation [11] where i and Δt were equal to 30 to determine the soil heat flux (G).

Statistical Methods

The daily data available to evaluate the predictive capacity of the different equations to estimate Class "A" pan evaporation extended over 4 years from 1 January 1971 to 31 December 1974.

The linear regression analyses were done by computer with the Utah State University Computer Services STATPAC library and a number of statistical test procedures were implemented to develop the evaluation (Neter and Wassermann, 1974; Middlebrooks, 1976).

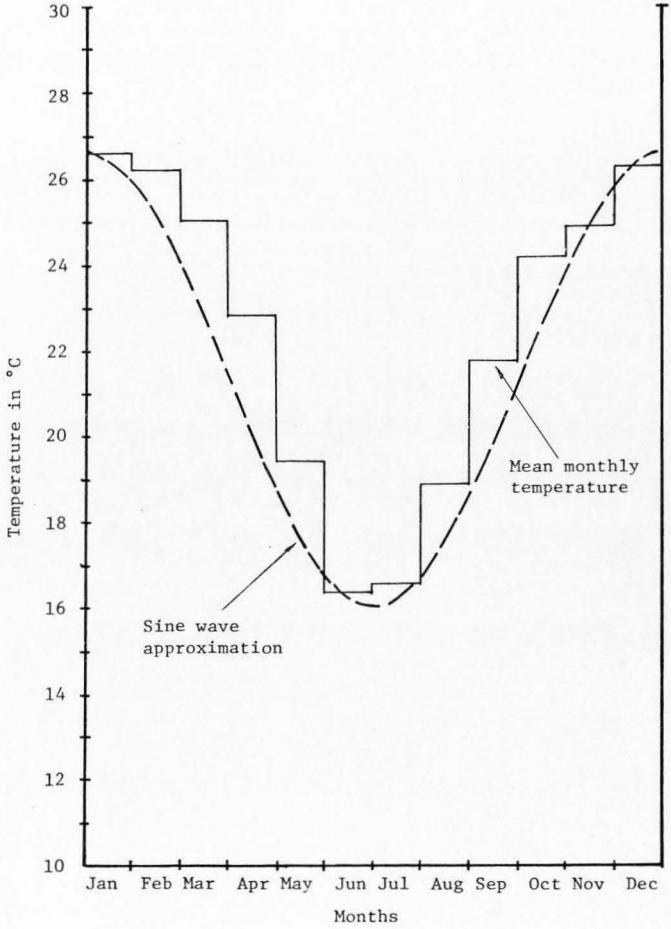

Figure 4. Mean monthly temperature (°C) compared to sine wave approximation for estimating expected daily mean temperatures.

Linear and nonlinear regression analysis

Measured and calculated radiation. The correlation between calculated solar radiation determined by the method described in Appendix A, and measured solar radiation with the Gunn-Bellani pyranometer was evaluated with linear and nonlinear regression analysis techniques.

Potential evaporation and Class "A" pan evaporation. In all, nine equations for determining potential evaporation were evaluated against Class "A" pan evaporation values using the data obtained from the Buffalo Range, Rhodesia, meteorological station. Four separate regression lines for each year and one for the 4 years were evaluated for each formula comparison.

Testing the equality of regression lines

The general linear test was used to evaluate the equality of the four separate yearly regression lines. This procedure is well documented in Neter and Wasserman (1974) and requires the development of an F test statistic from the analysis of variance data of the 4-year "pooled' and the separate single year linear regression analyses.

If the regressions lines are not equal, a T test statistic is used to evaluate the equality of the regression line coefficients.

Development of the confidence limits

Confidence bands by the Bonferroni method were calculated for each yearly regression line. The extreme upper and lower values over all 4 years for each method of calculating potential

evaporation were then plotted resulting in bands encompassing all four regression lines.

These confidence bands can be defined as the area in which the true regression lines will lie depending on the level of probability attributed to the development of the confidence intervals. The 0.05 level was used throughout this analysis.

Summary of Procedure

Table 1 lists the equations and variations in the parameters used to determine the potential evaporation values for correlation with measured Class "A" pan evaporation data.

The components of the nine equations evaluated are described in each of the sections relative to the specific type of equation. Four variations of Penman's equation, two of the Jensen-Haise equation, a single form of the Christiansen-Hargreaves extraterrestrial radiation equation and two of the Christiansen-Hargreaves solar radiation equation make up the nine equations.

Table 1. A listing of climatic variables used for computation in the potential evapotranspiration formulas

Equation	Radiation			Vapor pressure or relative humidity	Temper-ature	Pan evap.	Wind	Sun-shine	Eleva-tion
	Type	Albedo	Heat flux						
PENMAN 1	Calculated R_n	0.23	*	*	#	-	*	*	-
2	Calculated R_n	0.05	*	*	#	-	*	*	-
3	Gunn-Bellani R_n	0.23	*	*	#	-	*	-	-
4	Gunn-Bellani R_n	0.05	*	*	#	-	*	-	-
JENSEN 1	Calculated R_s	-	-	#	*	-	-	*	#
2	Gunn-Bellani R_s	-	-	#	*	-	-	-	#
CHRHAR 1	Calculated R_a	-	-	*	*	-	*	*	#
2	Calculated R_s	-	-	*	*	-	*	-	-
3	Gunn-Bellani R_s	-	-	*	*	-	*	-	-

The variables are listed either by values used, directly as daily units (*), or indirectly as seasonal or location constants (#).

RESULTS AND DISCUSSION

Comparison of Radiation Measurements

The evaluation of the two methods of radiation determination indicated a high correlation (Figure 5) between Gunn-Bellani measured radiation from the meteorological station at Buffalo Range, Rhodesia, and calculated radiation determined by using the technique described in Appendix A.

The calculated daily solar radiation values were compared with measured (Gunn-Bellani) daily radiation values on days where total sunshine was greater than 90 percent of total possible.

The range of calculated radiation was from 365 langleys/day to 680 langleys/day with the corresponding Gunn-Bellani radiation values ranging from 415 to 825 langleys/day. This results in approximately a 14 percent increase during winter and 21 percent increase in summer of the Gunn-Bellani radiation values over calculated radiation.

Quadratic and cubic regression equations were also evaluated. The quadratic model added little to the R^2 value, however the cubic model showed a 1 percent increase to an $R^2 = 0.98$. The slightly better fit of the cubic equation results in an increase in the difference between measured and calculated radiation during winter with a corresponding decrease during the summer. However, the magnitude of this variation over the linear model is less than 2 percent.

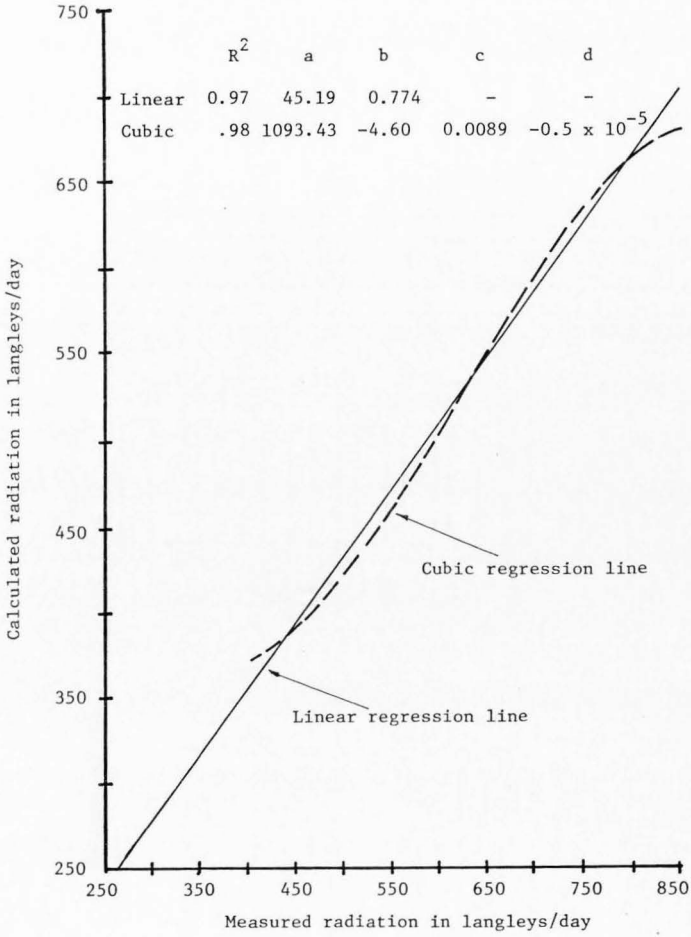

Figure 5. Plot of the correlation of measured (Gunn-Bellani) radiation and calculated radiation for Buffalo Range, Rhodesia, for the four years, 1971-1974.

Comparison of Pan Evaporation and Potential Evaporation Equations

Comparisons were made over 4 years by general linear regression techniques to determine how well the four potential evaporation equations, and variations of them, would predict pan evaporation.

Penman Equation

Figures 6, 7, 8, 9, and 10 show linear regression plots of potential evaporation as computed by four variations of Penman's equation (see Table 1) against Class "A" pan evaporation values. The data indicate that Penman's equations underestimated pan evaporation particularly when pan values exceed 5 mm day. This was particularly marked for PENMAN 1 and PENMAN 3 with high albedo values of 0.23. A closer relationship resulted when the albedo was lowered to 0.05, the free water value, as in PENMAN 2 and PENMAN 4. This supports previous studies where Penman's equation accurately predicts open water evaporation with albedo values varying from 0.06 to 0.09 (Robinson, 1966).

Effect of differing estimates of radiation and albedo

Figure 6 shows the variation in regression lines due to calculated and measured (Gunn-Bellani) radiation and the effect of two levels of reflectance (albedo).

The high correlation (R^2), see Figure 5, between the two methods of estimating solar radiation accounts for the consistent R^2 values listed in Figure 6.

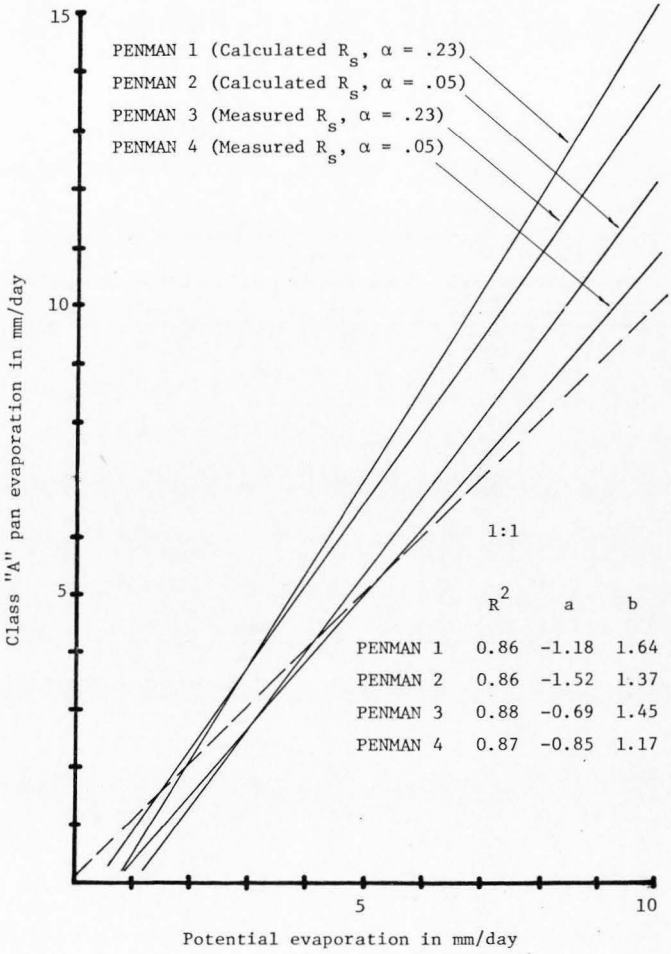

Figure 6. Pooled (1971-1974) linear regressions of Penmans potential evaporation compared to Class "A" pan for differing radiation and albedo values.

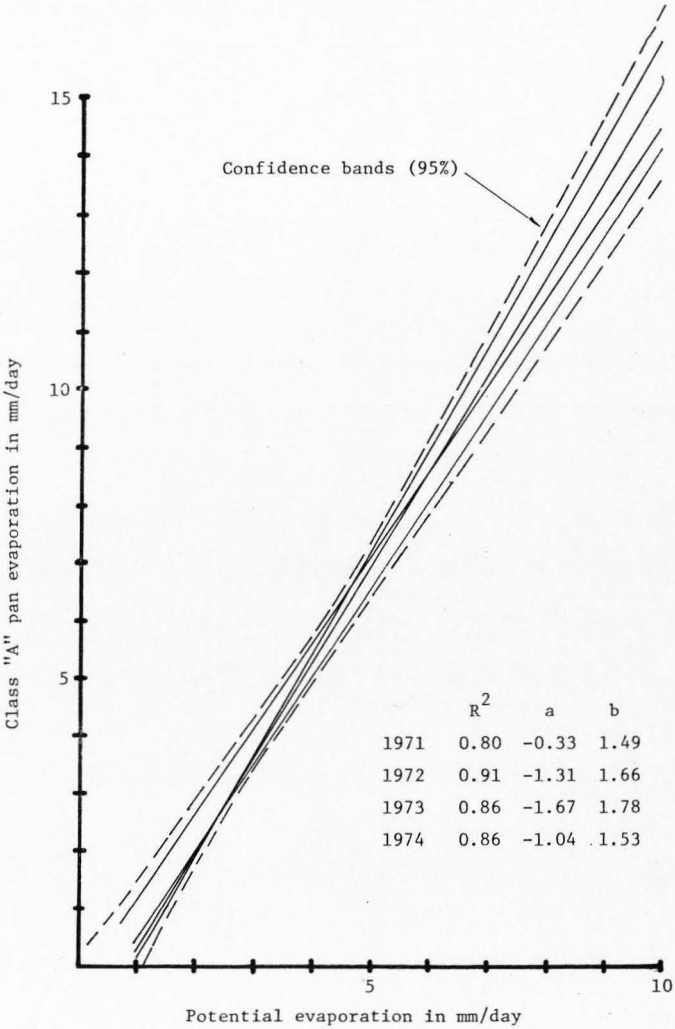

Figure 7. The yearly linear regression plots of Penmans potential evaporation (PENMAN 1) values against Class "A" pan evaporation, using calculated radiation and albedo = 0.23.

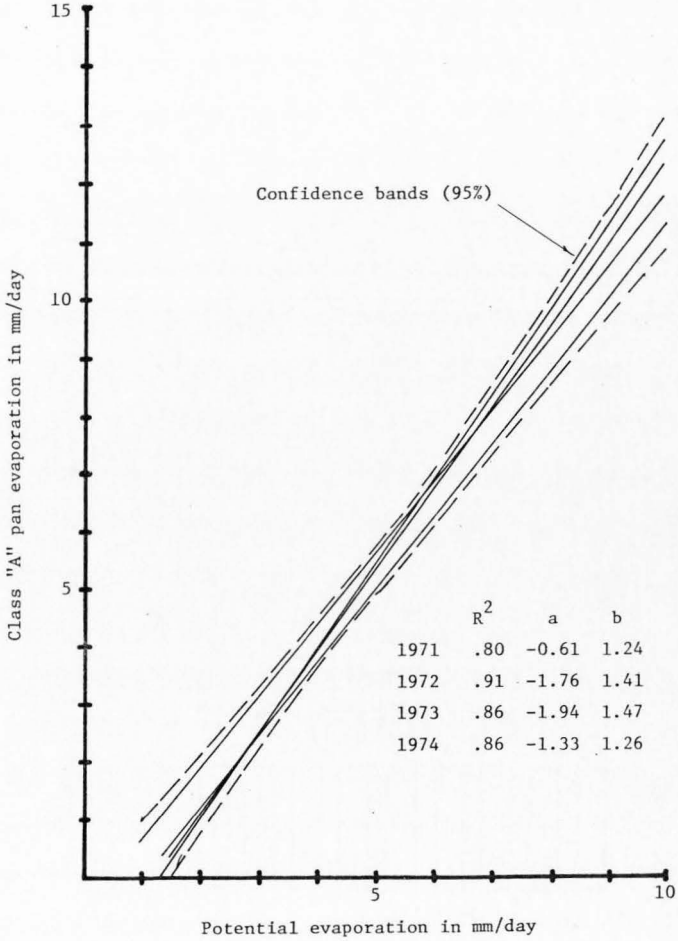

Figure 8. The yearly linear regression plots of Penmans potential evaporation values (PENMAN 2) against Class "A" pan evaporation, using calculated radiation and albedo = 0.05.

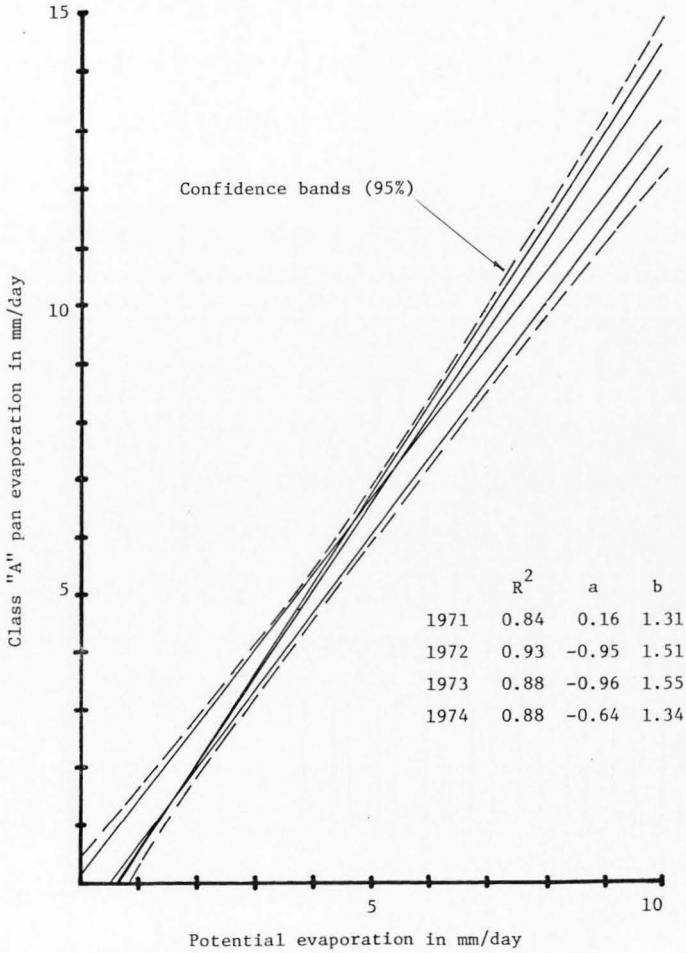

Figure 9. The yearly linear regression plots of Penmans potential evaporation (PENMAN 3) values against Class "A" pan evaporation, using measured (Gunn-Bellani) radiation and albedo = 0.23.

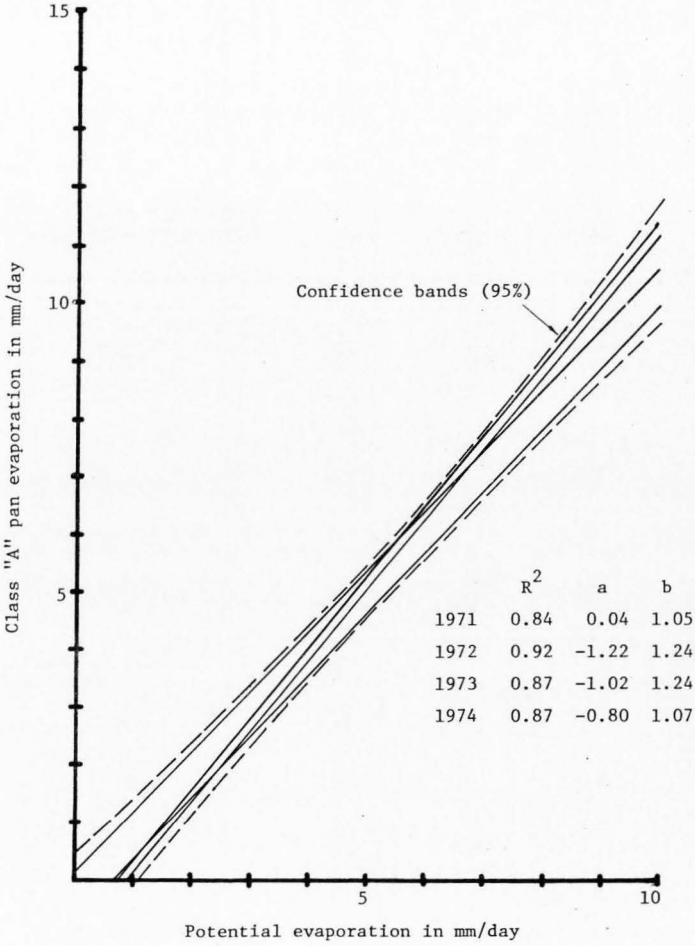

Figure 10. The yearly linear regression plots of Penman potential evaporation values (PENMAN 4) against Class "A" pan evaporation, using measured (Gunn-Bellani) radiation and albedo = 0.05.

Radiation. Comparison of the two different radiation inputs with the same level of albedo showed that the measured radiation lines had a lower slope than the computed radiation. The axis values of Figure 5 show measured radiation to be higher than computed, the result being that measured radiation has the effect of increasing Penman's potential evaporation value compared to using calculated radiation inputs.

Albedo. Penman's potential evaporation increased when the albedo was dropped from 0.23 to 0.05 as expected. This is evidenced by the decrease in slope from PENMAN 1 to PENMAN 2 and similarly PENMAN 3 to PENMAN 4. This indicates a relative decrease in slope of 20 percent and 24 percent which compares closely with the decrease of 18 percent in the albedo value.

Evaluation of annual regressions

The four estimates of potential evaporation determined by Penman's equation for individual years from 1971 to 1974 are detailed in Figures 7, 8, 9, and 10.

PENMAN 1. Figure 7 illustrates the four linear regression lines using calculated radiation and an albedo of 0.23. The four regression lines are bounded by a confidence interval determined from the confidence intervals of each of the separate regression lines. This procedure serves to indicate the range of variability that exists between years. The R^2 for all years was good except for 1971 with a value of 0.80.

Within the range of expected daily pan evaporation, the confidence intervals indicate a variation of less than 1 mm/day.

PENMAN 2. The albedo value was lowered to 0.05 with calculated radiation the same as PENMAN 1 (see Figure 8).

The characteristics are identical to PENMAN 1 but with a significant proportional lowering of the slope coefficient. Since the data is essentially the same, except in magnitude, to that obtained in PENMAN 1, the confidence intervals indicate a similar band about the expected values of pan evaporation of 1 mm.

PENMAN 3. In Figure 9, the albedo is the same as PENMAN 1 at 0.23; however measured radiation (Gunn-Bellani) replaces calculated radiation as the energy input.

The R^2 values are significantly higher than in PENMAN 1 or PENMAN 2. This could be due to the fact that actual measured radiation was used which would be more sensitive to cloud and atmospheric conditions than calculated radiation evaluated only from a sunshine percent factor.

The pattern of the four regression lines is similar to PENMAN 1 and PENMAN 2, with the 1971 regression line showing the least slope.

The confidence bands again indicate little spread over the range of seasonal expected pan evaporation.

PENMAN 4. Figure 10 shows the plot of four regression lines with radiation the same as PENMAN 3 but with the albedo lowered to 0.05.

The relationship to PENMAN 3 is the same as PENMAN 2 was to PENMAN 1. In comparison with PENMAN 1, PENMAN 2, and PENMAN 3, these regression lines have the least slope, the effect being that higher values of the horizontal PENMAN 4 axis are required to predict the expected values of pan evaporation. The effect of this is that the

higher values of PENMAN 4 indicate less accuracy with the width being as much as 2 mm.

Jensen-Haise Equation

Figures 11, 12, and 13 show the regression lines of the Jensen-Haise potential evaporation values correlated with pan evaporation.

The pooled data as plotted in Figure 11 shows much the same effect as in the Penman equations, with the higher values of measured radiation having the effect of decreasing the slope of the regression line. The R^2 are smaller than in the Penman equations.

Evaluation of annual regressions

JENSEN 1. This equation was evaluated using calculated radiation. The plot of the 4 years can be seen in Figure 12.

The R^2 ranges from 0.69 in 1971 to 0.81 in 1972 indicating some variability between years. This variability is reflected in the confidence limits about the regression lines which in the region of 10 mm expected pan evaporation has a vertical spread of about 2.5 mm. This would indicate some considerable inaccuracy in predicting pan evaporation from high calculated values of Jensen-Haise potential evaporation.

JENSEN 2. The effect of measured solar radiation is evident in Figure 12 where the increased values have decreased the slope of the regression lines.

The significant increase in the R^2 values can also be attributed to the use of radiation data that reflects actual atmospheric conditions

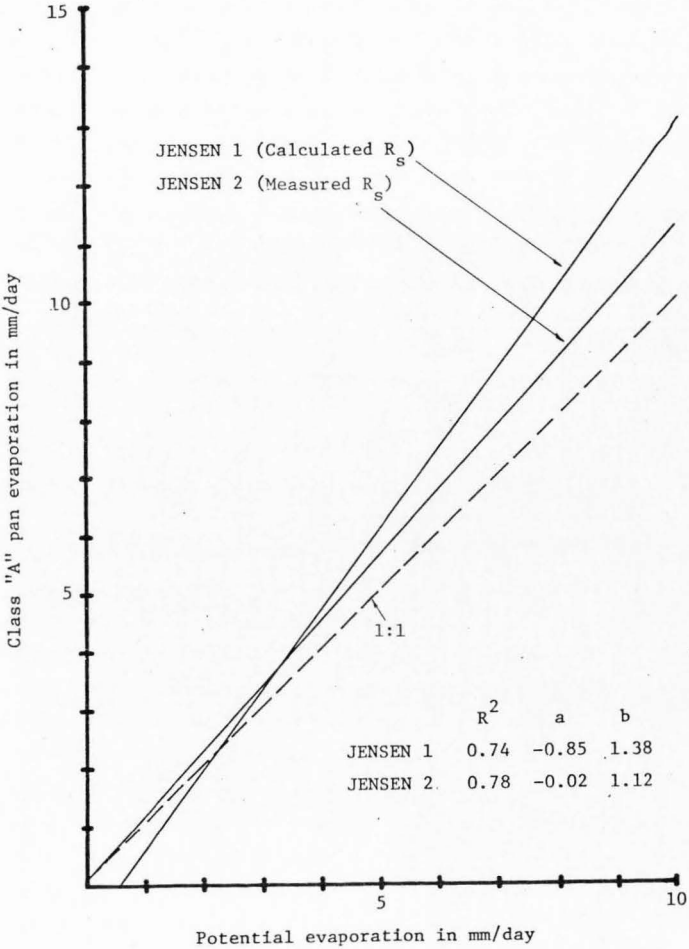

Figure 11. Pooled (1971-1974) linear regressions of Jensen-Haise potential evaporation values compared to Class "A" pan evaporation for differing radiation values.

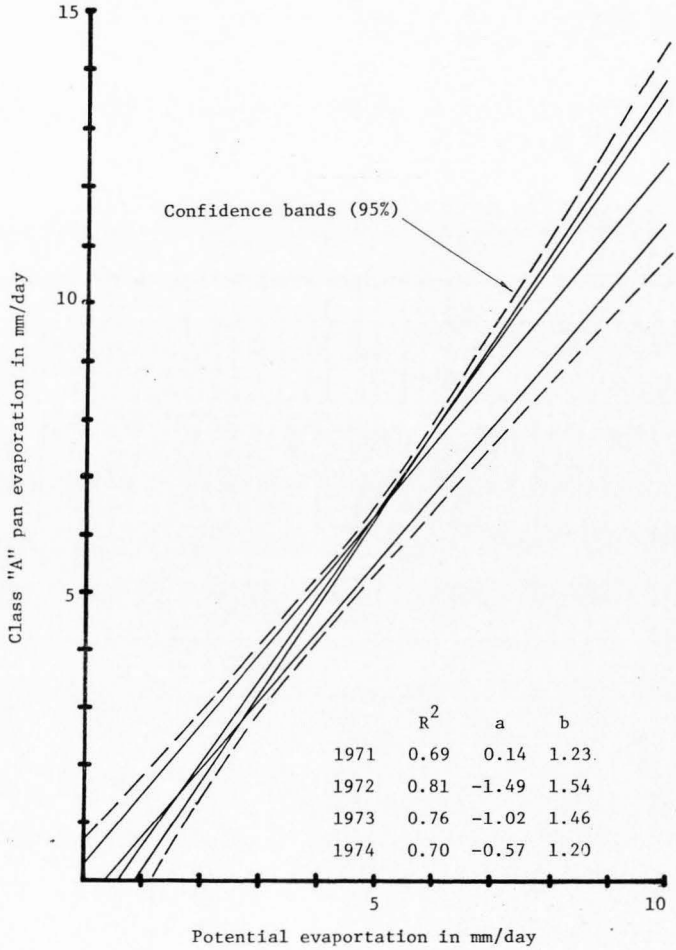

Figure 12. The yearly linear regression plots of Jensen-Haise potential evaporation (JENSEN 1) values against Class "A" pan evaporation, using calculated solar radiation.

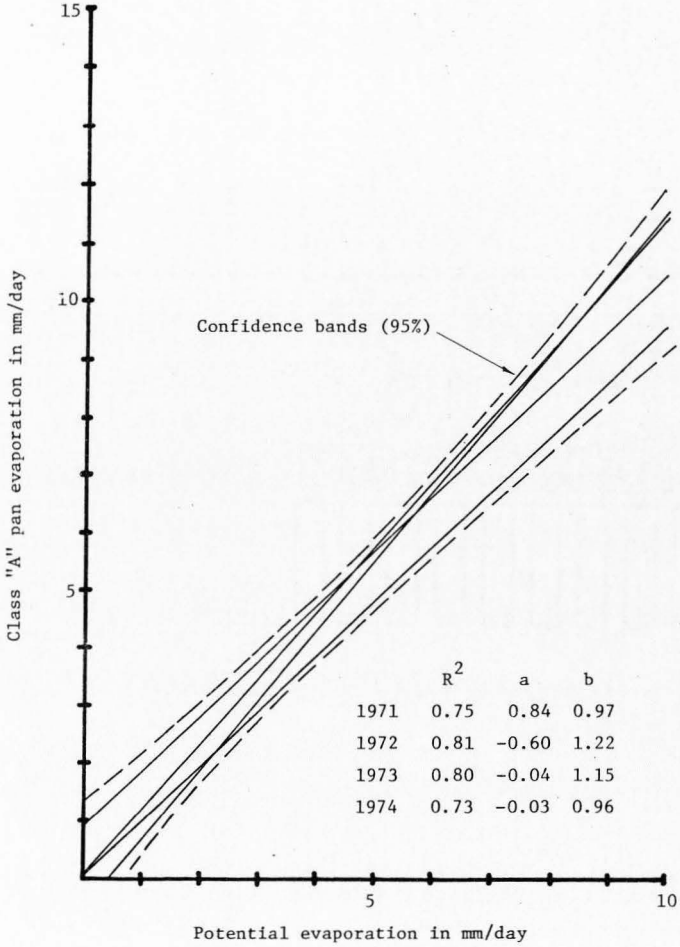

Figure 13. The linear regression plots of Jensen-Haise potential evaporation (JENSEN 2) values against Class "A" pan evaporation using measured radiation.

as explained in discussion of Penman 3. The variability is still evident by the broad confidence interval about the regression lines.

Christiansen-Hargreaves Equations

The linear regression analyses of the three Christiansen-Hargreaves equations are graphically represented in Figures 14, 15, 16, and 17.

Comparison of the equations

The results of the pooled 4-year data (Figure 14) shows higher R^2 values when compared to the Penman and Jensen-Haise equations. The three regression lines all have slopes which approach 1.0. The equation which uses extraterrestrial radiation, CHRHAR 1, for estimating potential evaporation comes close to having a 1:1 correlation with measured pan evaporation with a slope of 0.96.

The second equation which computes potential evaporation from solar radiation has been evaluated with calculated and measured solar radiation values, namely CHRHAR 2 and CHRHAR 3. The results were the same as noted with the Penman and Jensen-Haise equations. Measured radiation had a higher R^2 value and a decreased slope when compared to the regression line of the calculated radiation form of the equation.

Evaluation of annual regressions

CHRHAR 1. Figure 15 shows the results of using the extraterrestrial radiation form of the Christiansen-Hargreaves equation.

The R^2 ranges from 0.85 to 0.90 with the general slope of the regression lines approaching 1.0. The confidence bands indicate a spread of less than 1 mm over the entire range of expected evaporation.

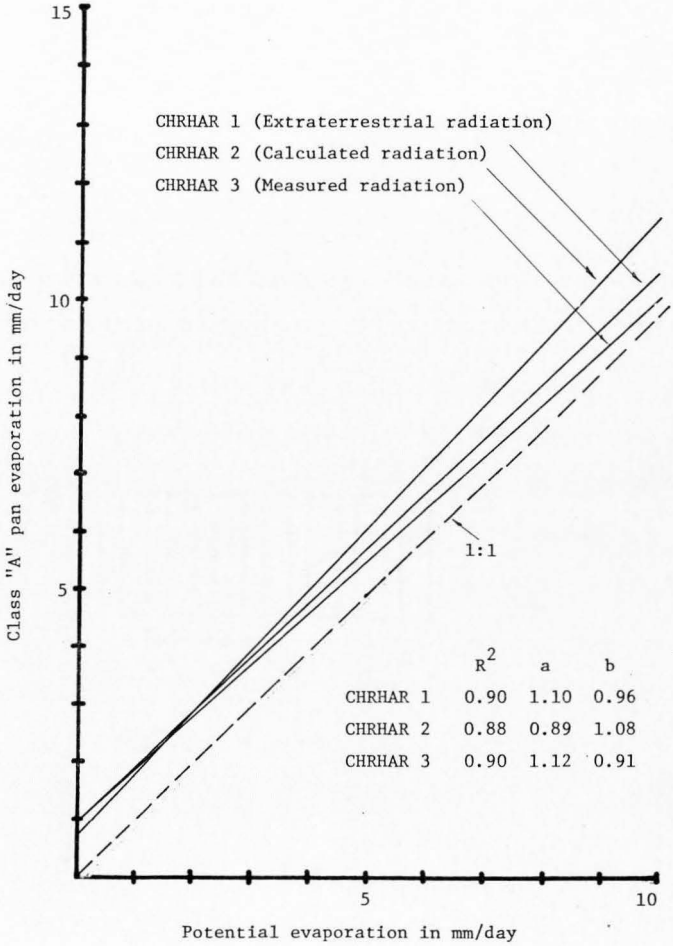

Figure 14. Pooled (1971-1974) linear regressions of the three Christiansen-Hargreaves potential evaporation values against Class "A" pan evaporation.

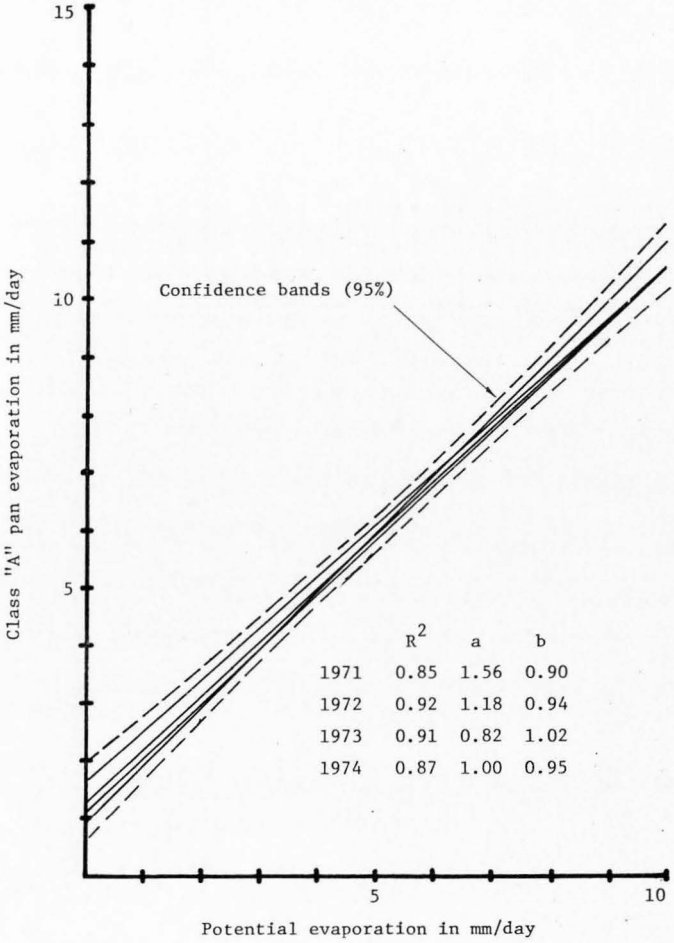

Figure 15. The yearly linear regression plots of Christiansen-Hargreaves (extraterrestrial radiation) potential evaporation values (CHRHAR 1) against Class "A" pan evaporation.

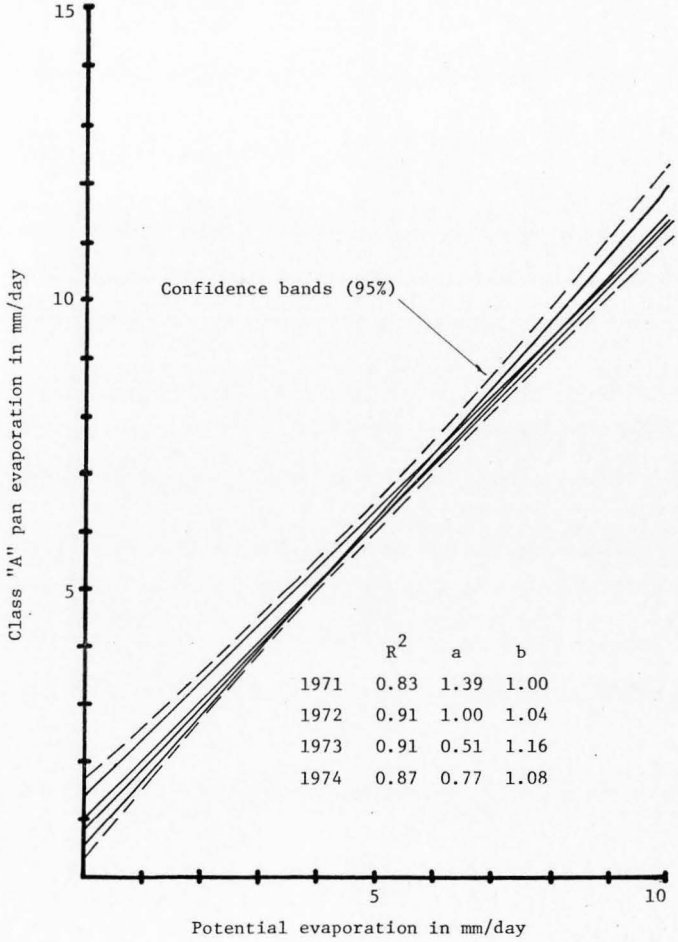

Figure 16. The yearly linear regression plots of Christiansen-Hargreaves (calculated solar radiation) potential evaporation values (CHRHAR 2) against Class "A" pan evaporation.

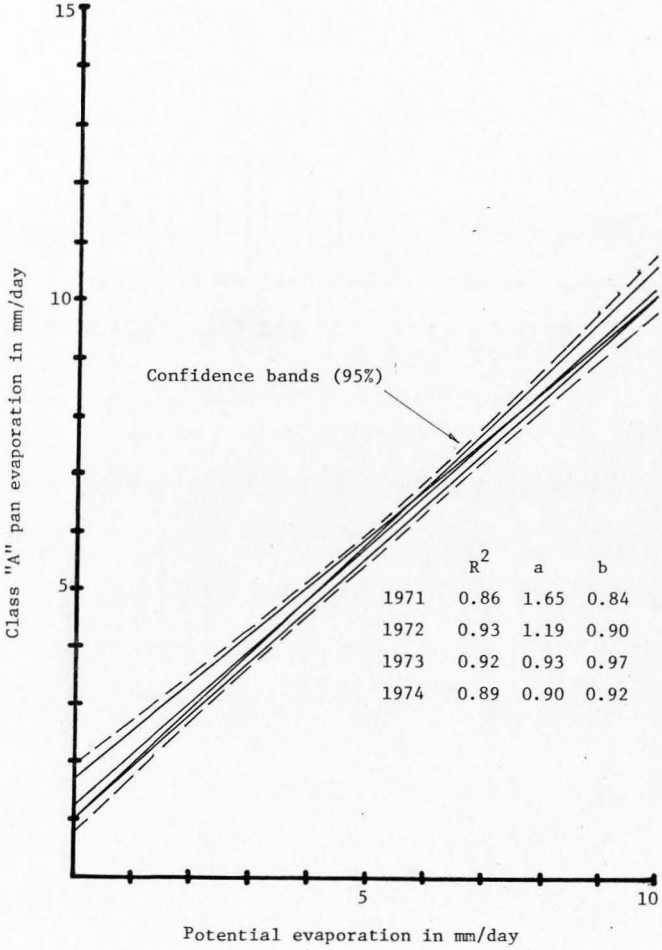

Figure 17. The linear regression plots of Christiansen-Hargreaves (measured solar radiation) potential evaporation values (CHRHAR 3) against Class "A" pan evaporation.

CHRHAR 2. The second Christiansen-Hargreaves equation uses solar radiation in the estimation of potential evaporation. Figure 16 shows the plot of the 4 years, 1971-1974, with calculated radiation as the radiation input.

The R^2 values vary from 0.83 to 0.91 and this is reflected in the range of confidence limits which do not exceed 1 mm over the range of expected Class "A" pan evaporation.

CHRHAR 3. Figure 17 shows the effect of using measured (Gunn-Bellani) radiation in the third form of the Christiansen-Hargreaves equations.

The effect of the measured radiation over calculated radiation is to increase the R^2 values and decrease the slope. This effect is the same as in the Penman and Jensen-Haise formulas. The slope is lowered from values of 1.00 to 1.16 in CHRHAR 2 (calculated radiation) to 0.84 to 0.97 when measured radiation is used.

Statistical Evaluation of the Regression Lines

Table 2 lists the F ratios determined by the general linear test. The F* statistic to evaluate variation in years is listed at the probability levels of 95 percent and 99 percent.

The calculated F ratios are all greater than the F* statistic. This leads to the conclusion that in all methods there is a significant difference between years. Therefore the "pooled" 4-year regression lines do not adequately predict the pan evaporation for all years.

Following the general linear test decision that there was a significant difference between years in the regression lines, the T

Table 2. The F ratios used to determine the equality of the regression lines between years

Method	F ratio
PENMAN 1	16.8
PENMAN 2	18.9
PENMAN 3	26.2
PENMAN 4	30.5
JENSEN 1	19.9
JENSEN 2	21.5
CHRHAR 1	7.8
CHRHAR 2	8.1
CHRHAR 3	11.1

F* at 0.95 = 2.1.
F* at 0.99 = 2.8.

test was used to determine whether the difference was due to one or other of the regression coefficients. Table 3 lists the T test values determined with the T* statistic evaluated at the 95 percent and 99 percent levels. The T test values greater than the T* statistic indicate significant differences between years.

From Table 3 it generally appears that there is a significant difference in slope and intercept. The few nonsignificant relationships are:

1. The Penman equations which indicate some conformity of slope between years 1971/1974 and 1972/1973.

2. The year comparisons 1973/1974, 1972/1974 and 1972/1973 show some equality in the intercept over most of the equations.

Table 3. Listing of T test values for evaluation of regression coefficients for significance between years

Method	1971-1972		1971-1973		1971-1974		1972-1973		1972-1974		1973-1974	
	a	b	a	b	a	b	a	b	a	b	a	b
PENMAN 1	4.92	3.58	5.68	5.32	3.48	0.61	1.85	7.53	1.65	3.32	3.19	5.21
2	5.46	4.26	5.53	5.04	3.35	0.41	0.89	1.52	2.41	4.26	2.87	5.04
3	6.56	5.32	5.84	5.75	4.63	0.86	0.10	1.24	2.11	4.82	1.88	5.29
4	7.11	6.08	5.31	5.40	4.62	0.10	1.11	0.03	2.71	0.76	1.75	0.76
JENSEN 1	5.88	5.31	3.97	3.73	2.54	0.56	1.73	1.40	3.59	6.03	1.66	4.38
2	6.32	5.84	3.88	4.22	3.93	0.14	2.47	1.60	2.54	5.88	0.03	4.29
CHRHAR 1	2.74	1.52	5.56	4.57	4.28	1.88	3.27	3.76	1.71	0.64	1.54	2.62
2	2.74	1.33	5.94	4.93	4.27	2.21	4.00	4.39	1.94	1.19	2.06	2.72
3	3.87	2.84	5.67	5.42	6.05	3.31	2.42	3.22	2.78	0,89	0.23	1.98

a = intercept test value, b = slope test value.
T* at 95 percent, 6 parameters and ∞ degrees of freedom = 2.41.
T* at 99 percent, 6 parameters and ∞ degrees of freedom = 2.95.

PART II

IRRIGATION SCHEDULING MODEL

PROCEDURE

Introduction

The Rhodesian sugar industry is ideally placed for the implementation of a centralized irrigation management service. The necessary data is available to determine daily estimates of potential evapotranspiration (or using Class "A" pan), crop water use coefficients, and desirable levels of optimum soil moisture depletion. These topics have all been discussed in some detail in the literature review, particularly in that Class "A" pan evaporation is used as the measure of potential evapotranspiration.

The computer program was written in Fortran IV for the Burroughs 6700 time share computer at Utah State University, Logan, Utah.

The development of the program was directed towards the functional aspects of irrigation scheduling and data retrieval, therefore no attempt was made to incorporate flexibility to extended regional application.

The program "SUGAR" was developed entirely on the principle of a soil water balance and does not include any specific portion of another program. The options incorporated in the program have been kept to a minimum and are included only to allow better control of the input and output data necessary to determine the validity of the irrigation scheduling procedure.

General Structure of the Program

This program has three sections:

1. The INPUT of field and climatic data
2. The COMPUTATION of the soil moisture balance
3. The OUTPUT of the predicted date of the next irrigation.

The program is well commented for ease of interpretation and together with a list of variable names is given in Appendix B.

The variable notation as used in the program will be used in the procedural writeup to aid in the interpretation of the computer program.

INPUT

The input data can be separated into three parts as follows:

1. Field, climate, and irrigation data
2. Options to enable the reinitiatising of variables
3. An option to list and plot data for specific fields and periods of time.

Field input

The field constants relate mainly to soil moisture characteristics, these are:

SLDP the soil depth in centimeters

SLTX the soil texture

TAM the available soil moisture in millimeters

PDL the soil moisture management allowed depletion level, in fractional percent, to which soil moisture can be extracted from the soil without moisture stress to the crop.

DIRI the amount of water applied at each irrigation in millimeters.

SSTR the initial soil moisture content at the start of crop growth.

The other characteristics of the field input data which make up the complete list are:

NUM the field identification

HECT the area in hectares

SLTX the soil texture

HRVM the month of harvest

HRVD the day of harvest.

The start of growth in this study is defined essentially as the time after which the crop becomes a factor in the evapotranspiration of moisture from the surface of the field. In a harvested (ratoon) crop this occurs on the day of the harvest, whereas in a newly planted crop, it occurs 10 to 20 days after planting when the crop emerges.

Climate input

From the wide range of data used to compute potential evapotranspiration, the following variables are read into the program:

RAD measured Gunn-Bellani solar radiation in langleys per day

TMM maximum temperatures in °C

TNN minimum temperatures in °C

RAIN in millimeters

WIND in miles per hour

RHUM the relative humidity in percent

EPAN the Class "A" pan evaporation which in the program is used as the measure of potential evapotranspiration.

Irrigation input

The day of irrigation for each field is determined by

NFI the field identification number

NMI the month of irrigation

NDI the day of irrigation

It should be noted that the irrigation levels are considered constant, although they will vary from field to field.

Option input

The following options were incorporated in the program:

1. The correction of selected values to the last update period, to allow a rerun of the same climate and irrigation input data.

2. The date of the next harvest can be altered. Although the program assumes the next harvest date to be on the same day the following year, the variable seasonal effects of climate and difficulties in obtaining optimum plant maturity will often require reassessment in the weeks prior to harvest.

3. Certain arrays at harvest are initialized to zero, such as seasonal rainfall, irrigation, evapotranspiration, and soil moisture variables.

The start of a new crop cycle always requires the use of the field input data sequence.

Plotting input

A listing of certain arrays and a plot of the available soil moisture can be called from diskfile storage for selected periods of time. The control variables for this are:

IIF the field identification number

JFN the last Julian day of the period selected

LIM the number of days in the period

The plot option then lists the following daily variables:

JDAY the Julian day of the year

CKC the crop coefficient

EVAP the daily Class "A" pan evaporation

ETA the evapotranspiration from crop, not considering the soil moisture content

AVMSX the daily total available soil moisture when soil moisture content is not considered

ETAM the evapotranspiration from the crop considering the limiting effects of soil moisture content

AVMS the daily total available soil moisture when soil moisture content is considered

EVAPE the expected daily Class "A" pan evaporation

ETAE the expected evapotranspiration not considering soil moisture content

ETAEM the expected evapotranspiration, considering soil moisture content

AVMSE the expected total available soil moisture considering soil moisture

WARN a control mechanism which identifies those days when soil moisture drops below ADPL

DEPSS the daily deficit in evapotranspiration due to the limiting effects of low soil moisture

RN rainfall

PRCP the effective precipitation, a value equal to or less than RN

DRRI an indicator defining the day of irrigation

OVER the loss of moisture to the system due to excess irrigation and/or rainfall

Computation of Water Balance

The water balance computational part of the program can be subdivided into two sections:

1. The current soil water balance computation involving the input of climate and irrigation data.

2. The expected soil water balance computation to predict the date of the next irrigation.

Factors of the soil water balance

This involves the interaction of a number of factors defined in the Literature Review. These factors are:

1. The characteristics of the soil.

2. The characteristics of crop water use.

With the parameters defined, the soil and water balance computation can be assessed.

Characteristics of the soil. du Toit (1968) describes the soils of the sugarcane growing areas in the southeastern Lowveld of Rhodesia. The soils are derived primarily from either gneisses of various ages and origins or basalts with minor intrusions of sandstone. The soils are formed under semiarid to arid conditions and are inherently fertile. Of the range of soils listed, the following three were chosen for inclusion in the model.

TRIANGLE PE1 SERIES (GNEISS). These soils comprise about 60 percent of the area currently under irrigation. The profiles usually consist of sandy loam to sandy clay loam topsoils over sandy clay loam and sandy clays. Soil depths range from 45 cm to 90 cm overlying soft weathering rock.

TRIANGLE P3 SERIES (GNEISS). These soils represent a small portion of the area under irrigation. Profiles are medium grained sands, over sands or loamy sands, over about 40 cm weakly weathered parent material. These soils occur in small outcrops and are often associated with lateritic gravel and sheets.

CHISUMBANJE SERIES (BASALT). Comprised of "self-churning" clays and heavy clays frequently overlying well weathered parent material. Soil depths vary from 30 cm to in excess of 200 cm. Commonly the soil depths vary between 30 and 90 cm.

Table 3 lists the soil data relevant to irrigation control for the three soils used in this study. The data for the Triangle PE1 and P3 soils were obtained from du Toit (1968) while that for the Chisumbanje basalts were obtained from unpublished data pertaining to preliminary soil surveys undertaken by the Soil Survey Section of the Department of Research and Specialist Services, Rhodesian Ministry of Agriculture, on behalf of the Rhodesian Sugar Association.

The three estimated field capacities shown in Table 3 were obtained from actual field measurements where suction-equivalent values were between one-tenth and one-third of an atmosphere. Wilting point was taken at 15 atmospheres suction.

Table 4. The soil moisture characteristics of three Rhodesian Lowveld soils

Soil category	Soil depth cm	Textural class	Water retention in mm per meter of soil		
			Estimated field capacity	Wilting point	Available water capacity
TRIANGLE PE1	0 -15	SaCL	280	120	160
	23 -33	SaC	266	141	125
	51 -61	SaC	286	173	113
	81 -91	Weathering rock	178	89	89
TRIANGLE P3	2.5-13	S	220	64	156
	25 -36	LS	204	65	139
CHISUMBANJE BASALTS	0 -91	C	380*	140*	240*

*Estimated values from unpublished data.

The moisture release curves of the soils in Table 3 over the range of available moisture are not published in du Toit's review of these soils. Accordingly, the relationship between water potential and available water depletion is as shown in Figure 3 (from Hagan and Haise, 1967).

The critical (matric potential) point in sugarcane appeared in the review of literature to vary from -0.25 bar to -2.0 bar. In this study a value of -1.0 bar has been adopted which leads to defining the approximate "critical points" of the three soil categories from Figure 3 as

1. Triangle PE1 = 50 percent depletion of total available moisture
2. Triangle P3 = 65 percent depletion of total available moisture

3. Chisumbanje Basalt = 40 percent depletion of total available moisture.

The differing levels of irrigation imposed on these soils in this study are typical of those currently used in the Rhodesian sugar industry. Table 4 shows the soil moisture parameters used in the program.

Table 4a. Approximate soil moisture characteristics of three Rhodesian Lowveld soils used in the model

Field number	Soil texture	Root zone (cm)	Total available moisture (mm)	No stress allowed depletion (mm)
1,6,11	Sandy clay loam	91	110.0	55.0
2,7,12	Sandy clay loam	51	69.0	34.5
3,8,13	Loamy sand	36	53.0	34.5
4,9,14	Clay	91	218.0	87.2
5,10,15	Clay	51	82.0	32.8

The root zone is determined by the maximum crop rooting depth of 91 cm (3 feet) if soil depth is not limiting, or less when depth becomes the limiting factor.

The no stress allowed depletion, ADPL, was obtained by multiplying the total available moisture, TAM, by the percent allowable depletion before the critical point is reached, DPL.

Characteristics of crop water use. As discussed in the Literature Review, optimum control of the soil water balance for maximum sucrose

yield per unit area was dependent upon the following two factors:

a. The CROP COEFFICIENT, which is the ratio of actual evapotranspiration to potential evaporation. This varies from 0.4 at the start of vegetative growth to 1.0 at full canopy.

b. The IRRIGATION COEFFICIENT which is the management required ratio of accumulated actual crop water use to accumulated potential crop water use. This is dependent upon the effects of low soil moisture on evapotranspiration.

The recommended irrigation control factors for sugarcane in Rhodesia reflect the combination of crop and irrigation coefficient according to Wilson and Metelerkamp (1974) and Lonsdale (1976).

For ease of analysis in the program, the crop and irrigation coefficients as defined are computed separately.

Crop coefficient. Table 5 has been modified from Wilson and Metelerkamp (1974) and Lonsdale (1976) to list only the monthly mean crop coefficients effective for all 12 months of the year.

The monthly crop factors do not adapt readily to computerized daily estimates of evapotranspiration. It is necessary, therefore, to calculate a continuous function to approximate the seasonal differences in the number of days between crop emergence and full canopy.

In the development of the function to determine the increasing crop coefficient, the range in time has been interpolated to vary from 50 days during the peak growth period of early summer to 100 days during the cool winter months.

Table 5. Monthly crop coefficients for sugarcane in Rhodesia showing the effects of different harvest dates

Harvest month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
January	0.40*	0.70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
February	1.00	0.40*	0.70	1.00	"	"	"	"	"	"	"	"
March	"	1.00	0.40*	0.60	0.80	1.00	"	"	"	"	"	"
April	"	"	1.00	0.40*	0.55	0.70	0.85	1.00	"	"	"	"
May	"	"	"	1.00	0.40*	0.55	0.70	0.85	1.00	"	"	"
June	"	"	"	"	1.00	0.40*	0.55	0.70	0.85	1.00	"	"
July	"	"	"	"	"	1.00	0.40*	0.55	0.70	0.85	1.00	"
August	"	"	"	"	"	"	1.00	0.40*	0.60	0.80	1.00	"
September	"	"	"	"	"	"	"	1.00	0.40*	0.60	0.80	1.00
October	"	"	"	"	"	"	"	"	1.00	0.40*	0.70	1.00
November	1.00	"	"	"	"	"	"	"	"	1.00	0.40*	0.70
December	0.70	1.00	"	"	"	"	"	"	"	"	1.00	0.40*

*Denotes month in which harvest occurred or visible crop growth began.

In the program, a subroutine, CROPKC, calculates the crop coefficient. A sine function, SK, was developed which, on the basis of the date of harvest is the slope of the linear line in Figure 18.

$$SK = 0.0036 \text{ Cos } (0.0172 \text{ (NNHRV)} + 0.7854) + 0.0097 \qquad [13]$$

where NNHRV is the date of harvest in Julian days and SK the slope of the line of the approximated linear function which calculates the crop coefficient, CKC.

$$CKC = 0.40 + SK \text{ (NDFHRV)} \qquad [14]$$

where CKC is the crop coefficient and NDFHRV is the number of days since growth began. When full canopy is reached, the increasing linear function is terminated and the crop coefficient is maintained at 1.0.

Irrigation coefficient. The subroutine, DEPLKC, computes the irrigation coefficient in three stages.

Stage 1: The period from harvest to full canopy.

Stage 2: The period from the start of full canopy until the onset of the drying off period.

Stage 3: The drying off period which varies in length of time depending on time of the year.

Table 6 lists the mean monthly irrigation coefficients as cited by Wilson and Metelerkamp (1974) and Lonsdale (1976).

Stage 1. During the period from harvest or crop emergence to full canopy, the irrigation coefficient, DKC, in the program has the same value as the crop coefficient.

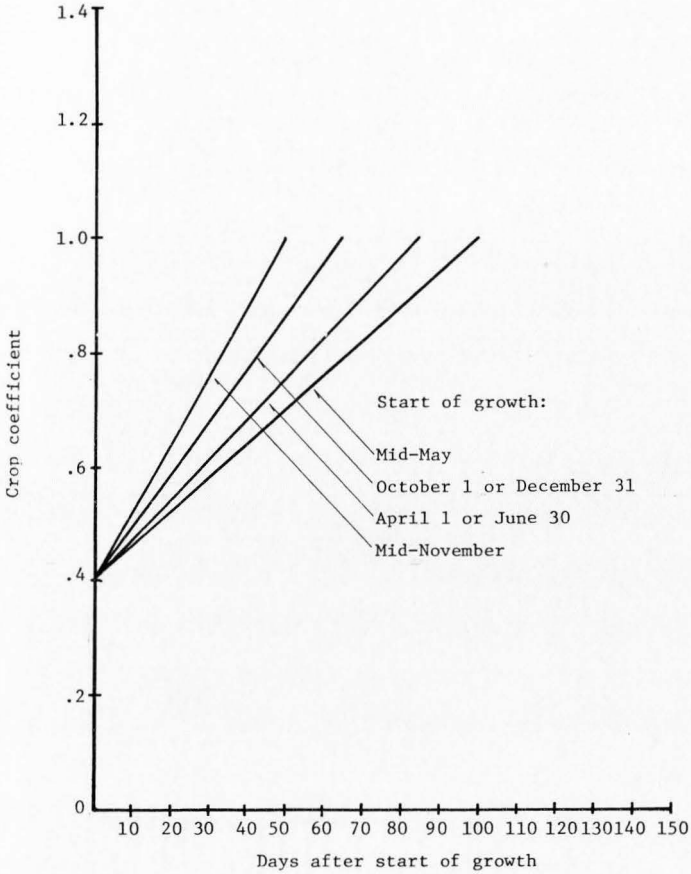

Figure 18. An illustration of the effect of different start of growth dates on the rate sugarcane takes to reach full canopy.

Table 6. Monthly irrigation coefficients for sugarcane in Rhodesia showing effects of different harvest dates

Harvest month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
January	1.00*	1.00	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.60
February	0.60	1.00*	1.00	0.85	"	"	"	"	"	"	0.85	0.60
March	0.60	0.60	1.00*	1.00	1.00	0.85	"	"	"	"	"	0.85
April	0.85	0.60	0.60	1.00*	1.00	1.00	1.00	0.85	"	"	"	"
May	"	0.85	0.60	0.60	1.00*	1.00	1.00	1.00	0.85	"	"	"
June	"	"	0.85	0.60	0.60	1.00*	1.00	1.00	1.00	0.85	"	"
July	"	"	0.85	0.60	0.60	0.60	1.00*	1.00	1.00	1.00	0.85	"
August	"	"	"	0.85	0.60	0.60	0.60	1.00*	1.00	1.00	0.85	"
September	"	"	"	"	0.85	0.60	0.60	0.60	1.00*	1.00	1.00	0.85
October	"	"	"	"	"	0.85	0.85	0.60	0.60	1.00*	1.00	0.85
November	0.85	"	"	"	"	"	"	0.85	0.60	0.60	1.00*	1.00
December	1.00	0.85	"	"	"	"	"	"	0.85	0.85	0.60	1.00*

*Denotes month in which harvest occurred or visible crop growth began.

Stage 2. From the full canopy date to the start of the drying off period, the irrigation coefficient is adjusted to meet the 0.85 criteria found by Gosnell (1970) and Gosnell and Lonsdale (1974) as the best management scheme to maximize sucrose.

Stage 3. From the start of drying off until harvest the irrigation coefficient is lowered to 0.60. The length of time required for drying off varies with time of year, and varies up to 90 days during the cool winter months and down to 30 days during the hot, dry early summer months. A study of the variation indicates that a simple symetric sine function will not provide an adequate fit. The rate at which the period declines from 90 days to 30 days as summer approaches is more rapid than the increase from the end of summer into winter. Two separate equations were, therefore, developed to calculate the number of days required for drying off, NDRYDY. The first equation is

$$NDRYDY = 30 \text{ Cos } (0.014 \text{ (NNHRV)} - 3.142) + 60 \qquad [15]$$

where NNHRV, the day of harvest, must be between 1 and 225 Julian days. The second equation, which follows, is used when the day of the approaching harvest is between 226 and 365 Julian days.

$$NDRYDY = 30 \text{ Cos } (0.0224 \text{ (NNHRV)} + 0.9599) + 60 \qquad [16]$$

The subroutine DEPLKC then determines whether the days remaining before harvest are less than or equal to the desired number of days for drying off and adjusts the irrigation coefficient down to 0.60 until harvest.

Computation of the soil water balance

With the relationship between plant, soil, and atmosphere determined, the soil water balance is computed by application of a simplified continuity approach.

The level of soil moisture, as discussed in the Literature Review, influences the rate of actual evapotranspiration. The following portion of the program balances two equations. The first equation which determines the water balance when evapotranspiration is not governed by the soil moisture content is

$$AVMSX = AMMSX - ETA + PRCP + DIRI \qquad [17]$$

where AVMSX is the soil moisture at the end of the period, AMMSX the soil moisture at the beginning of the period, ETA the actual evapotranspiration, PRCP the effective rainfall and DIRI the depth of irrigation.

The second equation applies where evapotranspiration is controlled by the soil moisture content, and it is

$$AVMS = AMMS - ETAM + PRCP + DIRI \qquad [18]$$

where AVMS is the soil moisture at the end of the period, AMMS the soil moisture at the beginning of the period, and ETAM the evapotranspiration, effective rainfall and irrigation applied during the period.

Evapotranspiration. The explanation of how the two evapotranspiration values, ETA and ETAM are evaluated and used is developed in the step by step procedure of the daily soil water balance which follows:

1. On the basis of the last harvest date (NNHRV), the crop coefficient (CKC) and the irrigation coefficient (DKC) are determined for each day.

2. From the climate input data, the potential evaporation value (EVAP) is initialized from measured Class "A" pan evaporation (EPAN).

3. Actual evapotranspiration (ETA), not considering the soil moisture content is determined by

$$ETA = CKC \times EVAP \qquad [19]$$

4. The program then determines whether the loss from available soil moisture (AMMS) has lowered soil moisture below the "critical level." The test value of remaining soil moisture (ETAS) is

$$ETAS = AMMS - ETA \qquad [20]$$

5. The allowable depletion percentage fraction (PDL) of the field input data is initiated into the allowable field depletion variable (ODPL), and is defined as the point beyond which soil moisture limits evapotranspiration. The conditional test to determine if ODPL has been exceeded is

$$IF\ ((FTAM - ETAS)/FTAM) \leq ODPL \qquad [21]$$

6. If the soil moisture reservoir has been depleted below ODPL, then the adjustment coefficient (EE) related to soil moisture content is computed as

$$EE = (ETAS/FTAM) \times (1/1 - ODPL) \qquad [22]$$

This adjusted coefficient is then used to correct potential evapotranspiration (ETA) which has not been adjusted for soil moisture to (ETAM) which is evapotranspiration adjusted for soil moisture content by

$$ETAM = ETA \times EE \qquad [23]$$

If soil moisture has not been depleted below ODPL by the test procedure, then

$$ETAM = ETA \qquad [24]$$

7. During the computation to determine actual evapotranspiration, (ETAM), both ETA and ETAM are summed to give cumulative values since harvest:

$$ETASS = ETASS + ETA$$

$$SETAM = SETAM + ETA$$

where ETASS is the sum of uncorrected potential evapotranspiration and SETAM is the sum of evapotranspiration corrected with respect to soil moisture content.

Rainfall and irrigation. The program then adjusts rainfall from climate input and irrigation from the irrigation input as follows:

8. Effective rainfall (PRCP) is evaluated on the assumption that no runoff occurs during the initial 20 mm of actual rainfall (RN) on any one day. Therefore,

$$PRCP = RN \qquad [25]$$

where actual rainfall is less than or equal to 20 mm. If actual rainfall exceeds 20 mm, the following assumed linear relationship between actual rainfall and effective rainfall is used:

$$PRCP = RN \times 0.375 + 12.5. \qquad [26]$$

Seasonal actual rainfall (SRN) and seasonal effective rainfall (SPRCP) are summed for each field.

9. The irrigation array (DRRI) is initialized from the irrigation input data for those fields irrigated during the updating period. DRRI determines the day of irrigation for individual fields. During computation of the soil water balance, the DRRI array is used to determine the day and fixed level of irrigation (FDIRI) for each field which is initialized into DIRI.

The program next evaluates the actual remaining soil moisture by equation [18], and the remaining soil moisture if soil water was not limiting by equation [17].

The significance of determining these two values is explained in some detail in the section dealing with the prediction of the next irrigation.

Effects of limiting soil moisture. This is assessed by testing whether the allowable depletion (ADPL) has been exceeded by a conditional statement.

$$IF\ (FTAM - AVMS) > ADPL \qquad [27]$$

The program records the days on which the allowable depletion was exceeded in the array (WARN), and computes the difference (DEPSS) between the two evapotranspiration values.

$$DEPSS = ETA - ETAM \quad [28]$$

Thus DEPSS is the shortfall of evapotranspiration due to the restrictions imposed by low soil moisture. These daily values of DEPSS are summed into the accumulated moisture deficit, DEPSM, which gives an indication of the effectiveness of the irrigation coefficient.

Distribution of excess moisture. A conditional statement determines whether the available moisture (AVMS) exceeds the total moisture holding capacity of the root zone (FTAM) by

$$OVER = AVMS - FTAM \quad [29]$$

where OVER is the loss of applied moisture. If no irrigation had occurred, this loss to deep penetration is attributed to rainfall (OVERP). If irrigation occurred with no rainfall, the loss is due to irrigation. Frequently irrigation and rainfall occur on the same day. The program differentiates the two, giving irrigation precedence over rainfall in determining what source was used to refill the soil moisture reservoir.

These losses give an indication of the magnitude of the moisture losses due to drainage and it is suggested that these losses can be used to modify irrigation control.

The program assumed that excess moisture will drain freely into the subsoil. This assumption is generally correct for the Triangle PE1 soils and the Chisumbanje Basalts. However, the Triangle P1 soils, in practice, are often associated with localized "perched" watertables, a fact which is ignored in this study.

The maximum possible amount of soil moisture depletion, FAVMSX, is computed next as

$$FAVMSX = FTAM - AVMSX \quad [30]$$

where soil moisture is not a limiting factor. The actual soil moisture depletion, FAVMS, is computed as

$$FAVMS = FTAM - AVMS \quad [31]$$

where soil moisture may be a limiting factor.

Prediction of next irrigation

The prediction portion of the program has been developed with no allowance being made for the probability of rain.

Determination of expected Class "A" pan evaporation. The sine wave function developed to predict potential evapotranspiration, EVAPE, from mean monthly values of Class "A" pan (Figure 19) is

$$EVAPE = 2.4 \text{ Cos } (0.0172 \text{ (JULIAN DAY)} + 0.2618) + 5.5. \quad [32]$$

Expected soil water balance. This program sequence is similar to the updating portion of actual soil moisture.

The maximum possible soil moisture depleted (FAVMSX) and actual depleted soil moisture (FAVMS) are initialized into the following variables,

$$ETAES = FAVMSX \quad [33]$$

$$ETAEMS = FAVMS \quad [34]$$

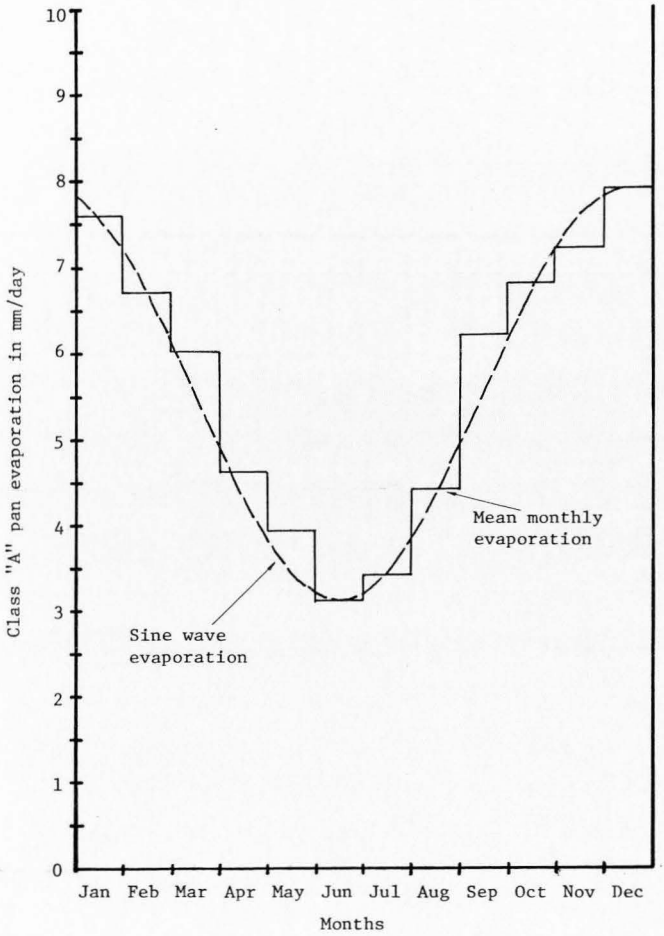

Figure 19. Mean monthly Class "A" pan evaporation compared to sine wave approximation for estimating expected daily values.

where ETAES is the sum of evapotranspiration expected when soil moisture is not limiting beyond the value ODPL, and ETAEMS is the sum of actual evapotranspiration expected taking into account that soil moisture is limiting beyond the value of ODPL.

The actual available soil moisture, AMMS, at the end of the update period is initialized into the expected soil moisture variable, AMMSE.

The prediction portion determines the day to day soil moisture balance identically to the update section as follows:

1. Expected evapotranspiration (ETAE) is determined by

$$ETAE = EVAPE \times CKC \qquad [35]$$

2. The program determines the expected soil moisture (ETAEX) and checks whether the soil moisture depletion ratio exceeds ODPL.

$$ETAEX = AMMSE - ETAE \qquad [36]$$

with the test function

$$IF((FTAM - ETAEX)/FTAM) \leq ODPL \qquad [37]$$

3. If depletion has exceeded ODPL, the expected soil moisture coefficient (EEE) is computed as

$$EEE = (ETAEX/FTAM) \times 2. \qquad [38]$$

4. When the expected soil moisture depletion level drops below ODPL, the actual expected evapotranspiration (ETAEM) is soil moisture dependent and is equal to

$$ETAEM = ETAE \times EEE. \qquad [39]$$

If, however, soil moisture has not been depleted below ODPL, then

ETAEM = ETAE. [40]

Determination of the next irrigation date. The program at this point tests whether irrigation is due. The following tests are incorporated in the prediction portion:

1. When the ratio (RETE) between the accumulated actual evapotranspiration (ETAEMS) and accumulated potential evapotranspiration (ETAES) is less than the irrigation coefficient (DKC) the program prints the date for the next irrigation.

2. Alternatively the irrigation system may be underdesigned and if actual accumulated evapotranspiration (actual soil water use) exceeds the depth of irrigation (FDIRI) that can be applied, the date of the next irrigation is printed.

Program Output

The printout of the data, Appendix D, is controlled by the three subroutines:

1. UPDATE. This subroutine lists the climatic data pertaining to the current update period.

2. ETLIST. Writes the sum and average values of past, recent, and future Class "A" pan evaporation information.

3. EXPECT. This subroutine writes out all the "UPDATING" and "PREDICTION" portions of the main program for each field.

The final portion of the main program lists whether any fields exceeded the allowable depletion during the update period. This serves as a check of the soil depletion.

RESULTS AND DISCUSSION

The scheduling model was compiled using 16 months of climatic data to determine the effectiveness of the methods of computation. The period extended from January 1, 1973 to April 30, 1974. The field characteristics were chosen to reflect the variance in soil type as described in the procedural section. The irrigation levels used are typical of systems in use in the irrigation of sugarcane in Rhodesia. Also pointed out is a summary of:

a. The climatic data during the update period, and

b. The Class "A" pan evaporation to date and expected 2-week mean values.

The following individual field data is also printed:

c. The field constants relating to soil moisture,

d. The crop and irrigation coefficients at the last date of the update period,

e. The date that the crop reaches full canopy,

f. The date of the last irrigation and the number and sum of irrigations to date,

g. A listing of the moisture losses due to either over-irrigation or excess rainfall, and

h. The accumulated evapotranspiration losses (moisture deficit) due to low soil moisture content.

Input of climate and irrigation data

The data run deck, listed in Appendix D, has several limitations as follows:

a. Only a maximum of 15 fields can be assessed. They must be initialized consecutively from 1-15.

b. At harvest the parameters for each field must be reinitialized for the start of the next season to avoid carryover errors.

c. When reinitializing current field printout data back to the last update period for correction purposes, all file data not in the printout will carry an error of magnitude determined by any difference which may have resulted from the corrections.

Flexibility in the input deck is exhibited by the following:

a. The number of climate cards entered per run is not fixed and depends largely on whether evaporation is above normal or if significant rainfall has occurred during the past few days.

b. Irrigation input has similar flexibility and includes multiple irrigation of the same period during a single update period.

Evaluation of the expected Class "A" pan evaporation function

The function for predicting Class "A" pan evaporation, equation [32], was evaluated for 4 years against measured values (see Figure 20). The prediction equation, which is approximated from 6 year monthly mean

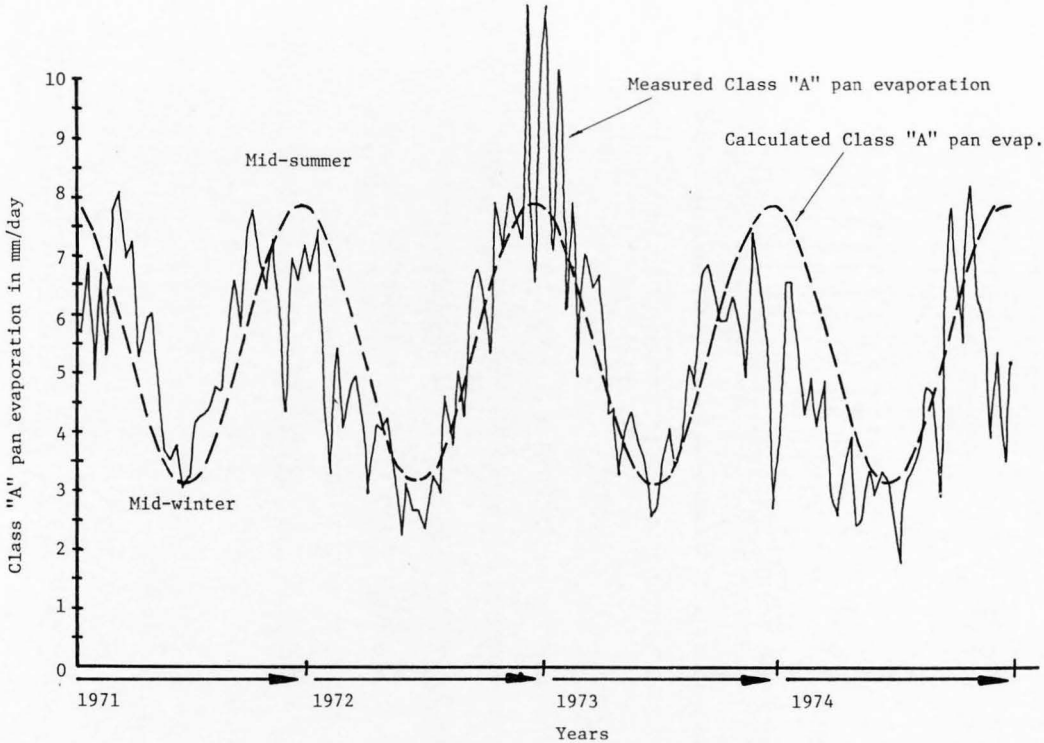

Figure 20. Plot of 10 day mean measured and calculated Class "A" pan evaporation from January 1, 1971 to December 31, 1974.

values, appears to fit actual values with good consistency from early winter well into early summer. However, the midsummer peaks show considerable variation from year to year. The rain, radiation, and sunshine input data for the 3 years 1971/1972, 1972/1973, and 1973/1974 is summarized in Table 7.

The summer periods of the 1971/1972 and 1973/1974 seasons had higher than normal rainfall and lower than normal radiation and sunshine. The summer period of 1972/1973 had the opposite seasonal effects. Thus, it can be concluded that the prediction function does not adequately estimate Class "A" pan evaporation during the summer months when rain, radiation, and sunshine are not close to normal.

Soil water stress function

This function, which assesses the effect of low soil moisture on actual evapotranspiration, equations [20] to [23] and [36] to [39], was evaluated graphically.

Figure 21 compares the rate of actual soil moisture depletion on on the Triangle PE1 sandy clay loams of fields 2, 7, and 12 from January 1, 1974. Figures 22 and 23 illustrate the same relationships for Triangle P3 loamy sands (fields 3, 8, and 13) and Chisumbanje Basalt clays (fields 5, 10, 15).

Although the clay has the higher available soil moisture values, it is the first to reach the critical level of depletion. The Triangle P3 loamy sand has a higher proportion of readily available soil water but rapidly limits evapotranspiration when the critical level is passed.

Table 7. Monthly total values of rain, radiation and sunshine for the 6 month periods October-March for the years 1971/1972, 1972/1973, and 1973/1974

	1971/1972			1972/1973			1973/1974		
	Rain (mm)	Radiation (lgly/day)	Sunshine (hours)	Rain (mm)	Radiation (lgly/day)	Sunshine (hours)	Rain (mm)	Radiation (lgly/day)	Sunshine (hours)
October	52.4	16530	244.1	28.4	16724	254.8	29.2	16078	239.8
November	74.2	16201	212.0	12.2	17962	266.7	94.9	17111	235.1
December	83.7	19765	272.3	41.5	19968	294.3	406.3	14583	165.1
January	262.4	16289	193.3	99.9	18859	285.7	33.1	20237	294.1
February	174.8	16244	207.0	49.9	16483	243.8	184.4	14177	174.4
March	98.2	15898	214.9	46.0	18264	285.9	102.2	16003	219.0
Sum	705.7	100927	1343.6	277.9	108260	1631.2	850.1	98189	1327.5
Long time averages	365	103722	1520.6	365	103722	1520.6	365	103722	1520.6

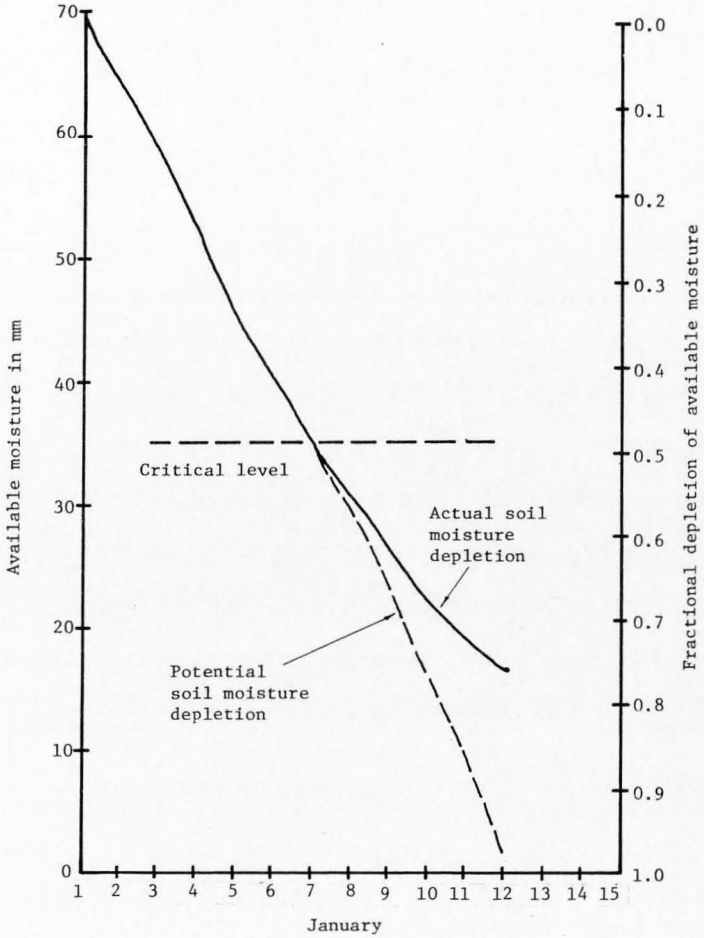

Figure 21. Actual and potential soil moisture curves for a Triangle PE 1 sandy clay loam soil as computed by the soil moisture stress function from January 1, 1974.

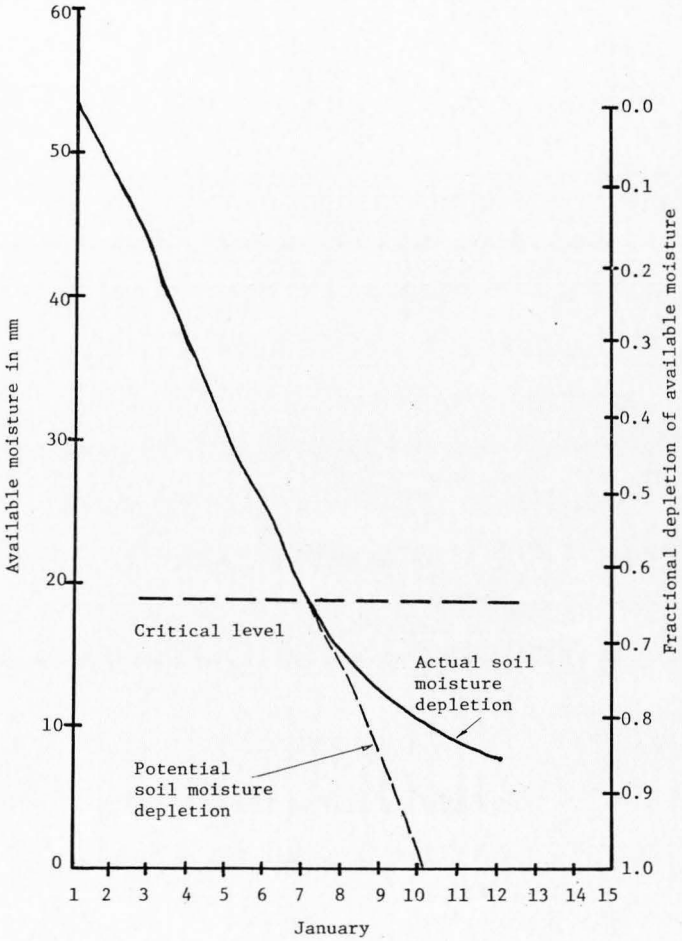

Figure 22. Actual and potential soil moisture curves for a Triangle P3 loamy sand as computed by the soil moisture stress function from January 1, 1974.

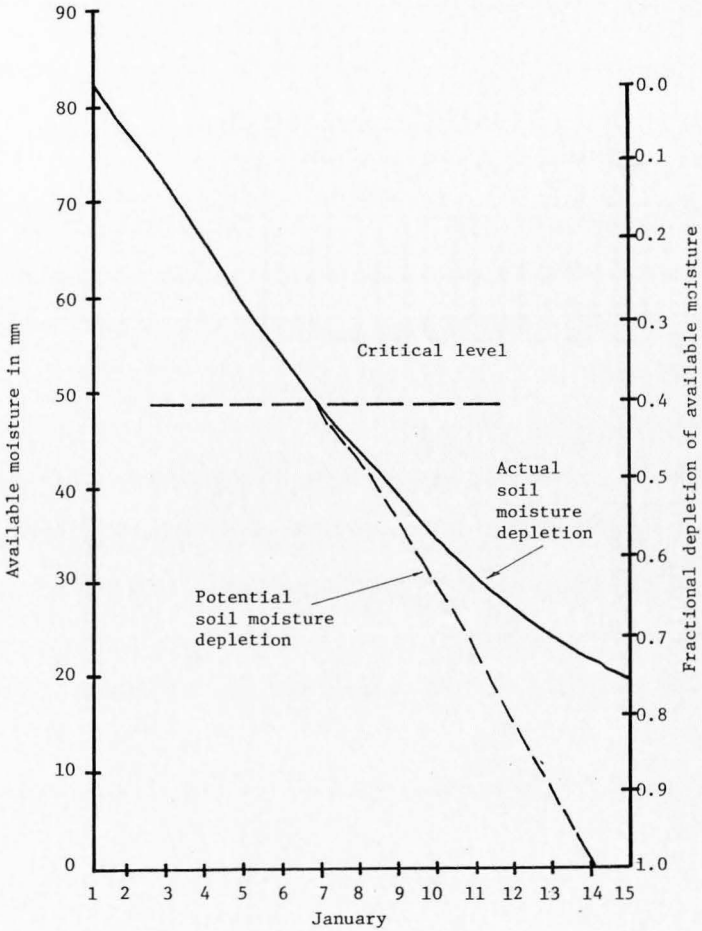

Figure 23. Actual and potential soil moisture curves for a Chisumbanje basalt clay as computed by the soil moisture stress function from January 1, 1974.

The soil water stress function is not adequate as wilting point is approached. Available soil moisture erroneously approaches an asymptote, the value being each day equal to the pan evaporation value.

Assessment of the water balance computations

Tables 8 and 9 are presented to illustrate the daily data necessary to compute the soil water balance. The data shows actual and predicted listings of evapotranspiration and the available soil moisture.

The date for Field 8 from June 13 to June 27, 1973 is shown in Table 8. It indicates the increasing daily crop coefficient expected during this period. The predicted evapotranspiration and soil water limiting evapotranspiration columns indicate how by June 26 the ratio of their accumulated totals is lower than 1.0, the desired irrigation coefficient. The program calls for an irrigation on this date which took place as indicated in the column of actual available soil moisture. Further details of the schedule printouts are given in Appendix C for this same period.

The effectiveness of the irrigation coefficient when it is lowered to 0.85 is illustrated by the data in Table 9. Ratios of the accumulated totals of predicted evapotranspiration and predicted soil water limiting evapotranspiration determine that irrigation was predicted for Feb 7 when the ratio dropped below 0.85. However, an update occurred because of the occurrence of some days of low pan evaporation (see Appendix C for this period). The update of soil

Table 8. Listing of actual and predicted soil moisture for the period June 12 to June 27, 1973

Field No. 8 Date	Crop[1] coeff.	Actual water balance: Class "A" pan evap. (mm)	Actual water balance: Evapo-trans. (mm)	Actual water balance: Avail. soil moisture (mm)	Predicted water balance: Class "A" pan evap. (mm)	Predicted water balance: Potential evapo-trans. (mm)	Predicted water balance: Actual evapo-trans. (mm)	Predicted water balance: Accum. ratio ETa/ETp	Predicted water balance: Available soil moisture (mm)
June 12	0.59	2.20	1.30	45.31	3.11	0.00	0.00	-	0.00
13	0.60	1.40	0.83	44.48	3.10	1.85	1.85	-	43.46[2]
14	0.60	2.30	1.38	43.09	3.10	1.87	1.87	1.0	41.60
15	0.61	2.50	1.52	41.57	3.10	1.88	1.88	1.0	39.71
16	0.61	2.60	1.60	39.98	3.10	1.90	1.90	1.0	37.81
17	0.62	2.80	1.74	38.24	3.10	1.92	1.92	1.0	35.89
18	0.63	4.20	2.63	35.61	3.10	1.94	1.94	1.0	33.94
19	0.63	3.50	2.21	33.40	3.10	1.96	1.96	1.0	31.98
20	0.64	3.80	2.43	30.97	3.10	1.98	1.98	1.0	30.00
21	0.64	3.20	2.06	28.91	3.11	2.00	2.00	1.0	28.00
22	0.65	2.60	1.69	27.72	3.11	2.02	2.02	1.0	25.97
23	0.66	1.80	1.18	26.04	3.12	2.05	2.05	1.0	25.17
24	0.66	2.20	1.46	24.58	3.12	2.07	2.07	1.0	23.10
25	0.67	3.70	2.48	22.10	3.13	2.09	2.09	1.0	21.01
26	0.68	3.00	2.03	20.08	3.13	2.11	2.11	1.0	18.90
27	0.68	1.30	0.89	53.00	3.14	2.14	1.93	0.99	-

[1]The irrigation coefficient is equal to 1.0 throughout this period.
[2]This value is the expected available soil moisture the first day after the update period.

Table 9. Listing of actual and predicted soil moisture for the period January 30, 1974 to February 15, 1974

Field No. 8 Date	Crop[1] coeff.	Actual water balance					Predicted water balance				
		Class "A" pan evap.	Potential evapo-trans.	Potential available soil moisture	Actual evapo-trans.	Available soil moisture	Class "A" pan evap.	Potential evapo-trans.	Actual evapo-trans.	Accum. ratio ETa/ETp	Available soil moisture
Jan 30	1.00	2.70	2.70	53.00	2.70	53.00	7.21	0.00	0.00	-	0.00
31	1.00	4.00	4.00	51.40	4.00	51.40	7.18	0.00	0.00	-	0.00
Feb 1	1.00	6.70	6.70	44.70	6.70	44.70	7.15	7.15	7.15	-	44.25
2	1.00	6.70	6.70	38.00	6.70	38.00	7.12	7.12	7.12	1.0	37.13
3	1.00	4.20	4.20	34.90	4.20	34.90	7.09	7.09	7.09	1.0	30.04
4	1.00	5.80	5.80	29.10	5.80	29.10	7.06	7.06	7.06	1.0	22.98
5	1.00	4.50	4.50	24.60	4.50	24.60	7.03	7.03	6.04	0.97	16.94
6	1.00	6.50	6.50	18.10	6.34	18.26	7.00	7.00	3.75	0.90	13.19
7	1.00	5.90	5.90	13.20	3.93	15.33	6.96	6.96	4.24	0.94	14.02[2]
8	1.00	6.40	6.40	29.46	3.08	34.91	6.93	6.93	2.65	0.87	11.37
9	1.00	3.10	3.10	53.00	3.10	53.00	6.90	6.90	1.66	0.80	0.00
10	1.00	2.80	2.80	51.40	2.80	51.40	6.86	6.86	6.86	1.00	46.14[2]
11	1.00	2.10	2.10	49.40	2.10	49.40	6.83	6.83	6.83	1.00	39.31
12	1.00	5.10	5.10	44.30	5.10	44.30	6.79	6.79	6.79	1.00	32.51
13	1.00	0.90	0.90	53.00	0.90	53.00	6.76	6.76	6.76	1.00	25.76
14	1.00	2.80	2.80	53.00	2.80	53.00	6.72	6.72	6.72	1.00	19.03
15	1.00	3.10	3.10	50.00	3.10	50.00	6.69	6.69	6.69	1.00	46.31[2]

[1]The irrigation coefficient is equal to 0.85 throughout the period.
[2]This value is the expected available soil moisture the first day after the update period.

moisture led to a new prediction date of Feb. 9 is indicated by the ratios in Table 9 and the printout in Appendix C. The occurrence of rain delayed irrigation and a new update on Feb. 14 led to a new prediction date on Feb. 22.

Effects of different soils and irrigation regimes

The ability to apply the irrigation coefficient to the control of irrigation scheduling is dependent on whether the depth of irrigation applied is sufficient to maintain adequate soil moisture levels.

Figures 24, 25, 26, 27, and 28 show the effects of low and high levels of irrigation relative to individual field soil moisture characteristics.

Field No. 6 in Figure 24 shows the control of soil moisture on the sandy clay loam soils of the Triangle PE1 category. The irrigation level of 45 mm is less than the allowed depletion of 55 mm. Table 10 shows how the prediction of the next irrigation is controlled. When the level of predicted soil moisture depletion is greater than the level of irrigation, the program predicts the next irrigation date. Figure 24 shows the plot of available soil moisture. The level of soil moisture is maintained between total available and the allowable depletion.

Figure 25 illustrates the effect when the level of irrigation exceeds the allowable depletion and the crop goes into the desired stress for the Triangle PE1 soil. The hashed line below the allowable depletion level indicates the level of available moisture if soil moisture was not a limiting factor on evapotranspiration. Table 11 lists the data used to plot Figure 25, and determines the accumulated

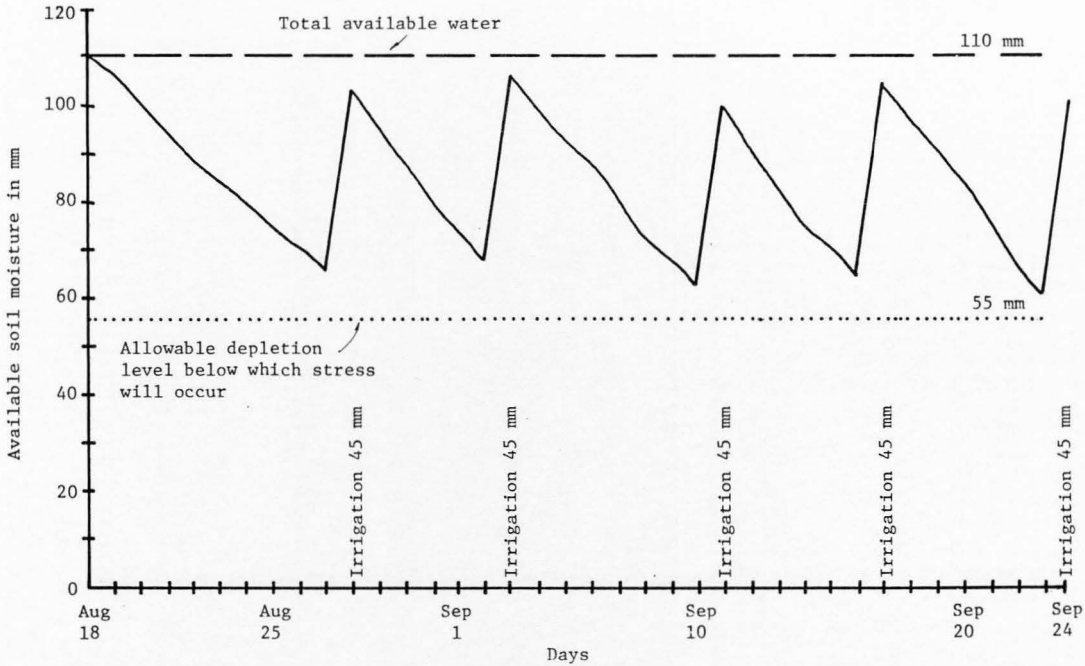

Figure 24. Available soil moisture in Field No. 6 for the period August 18 to September 24, 1973.

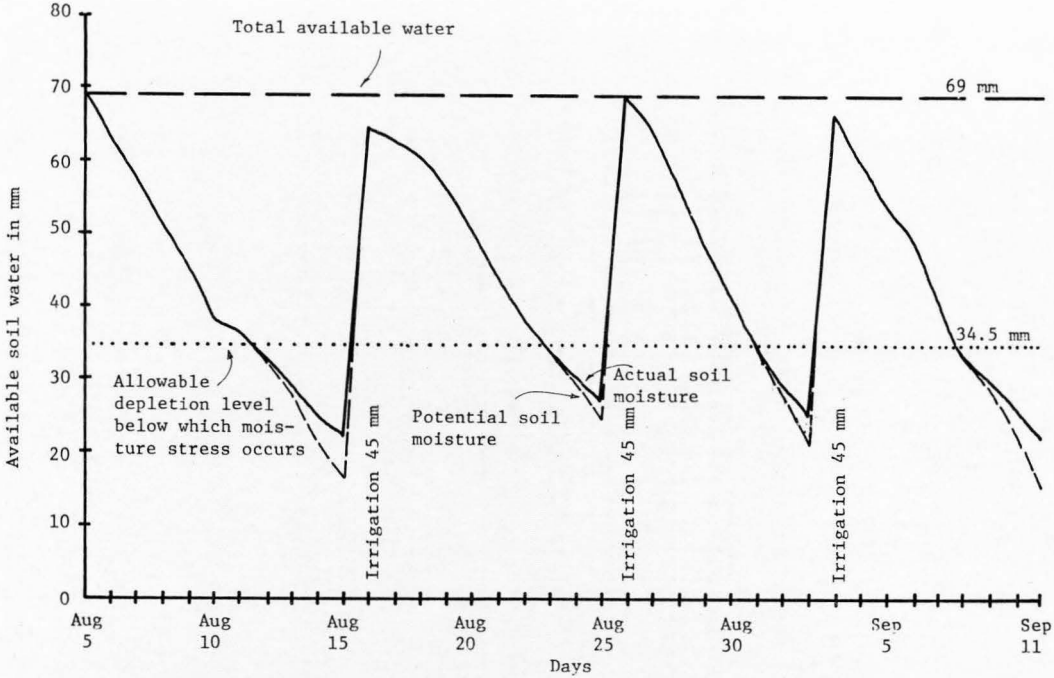

Figure 25. Available soil moisture in Field No. 7 for the period August 10 to September 11 showing the effects of limiting soil moisture.

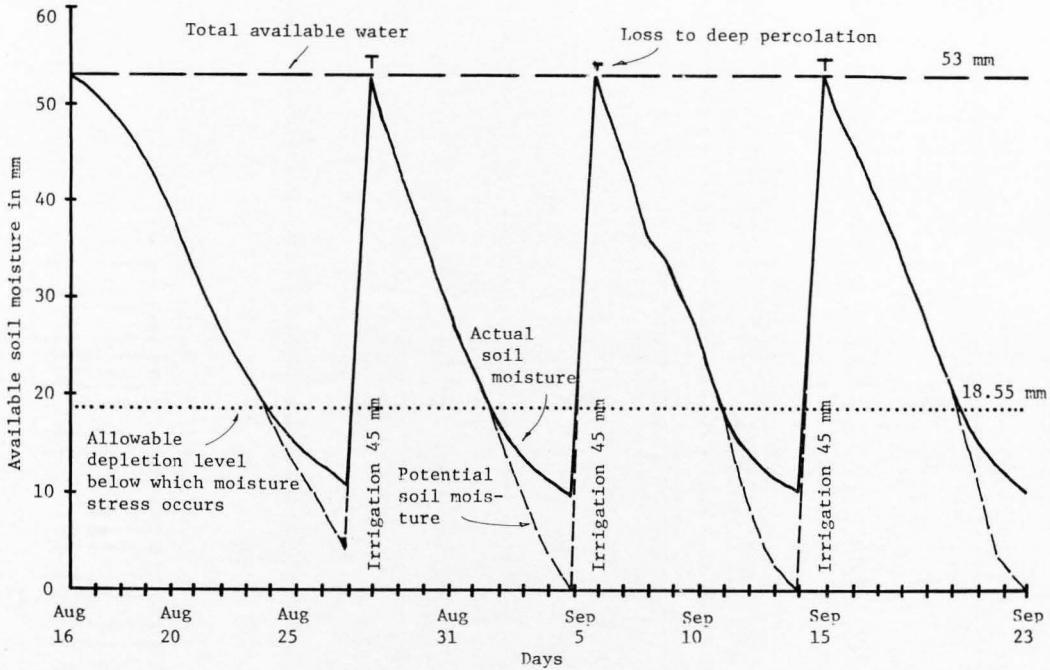

Figure 26. Available soil moisture in Field No. 8 for the period August 16 to September 23 showing effects of limiting soil moisture.

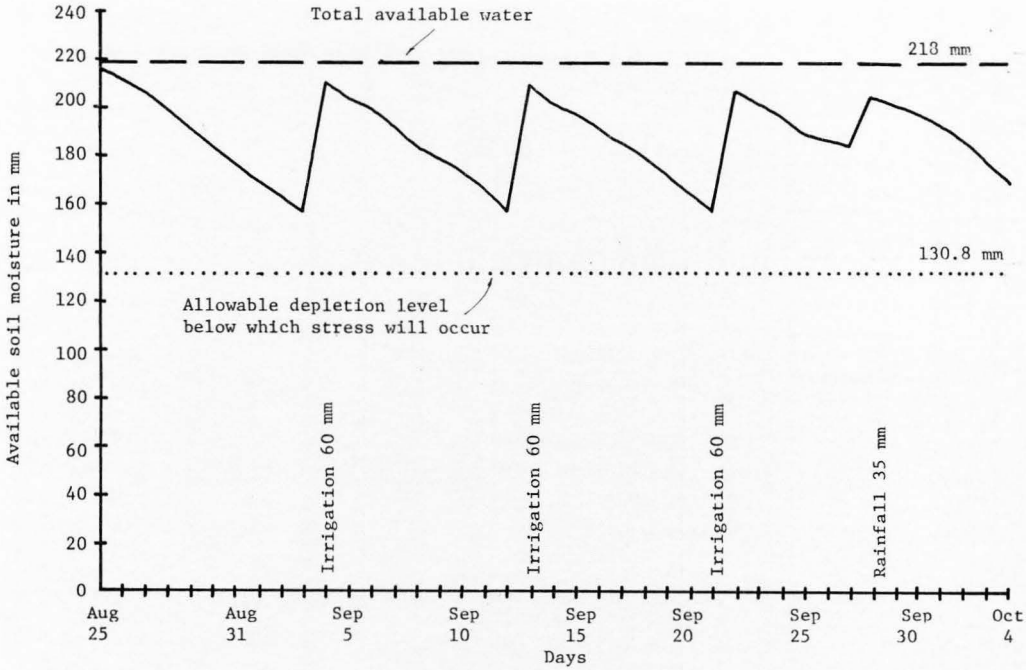

Figure 27. Available soil moisture in Field No. 9 for the period August 25 to October 4, 1973.

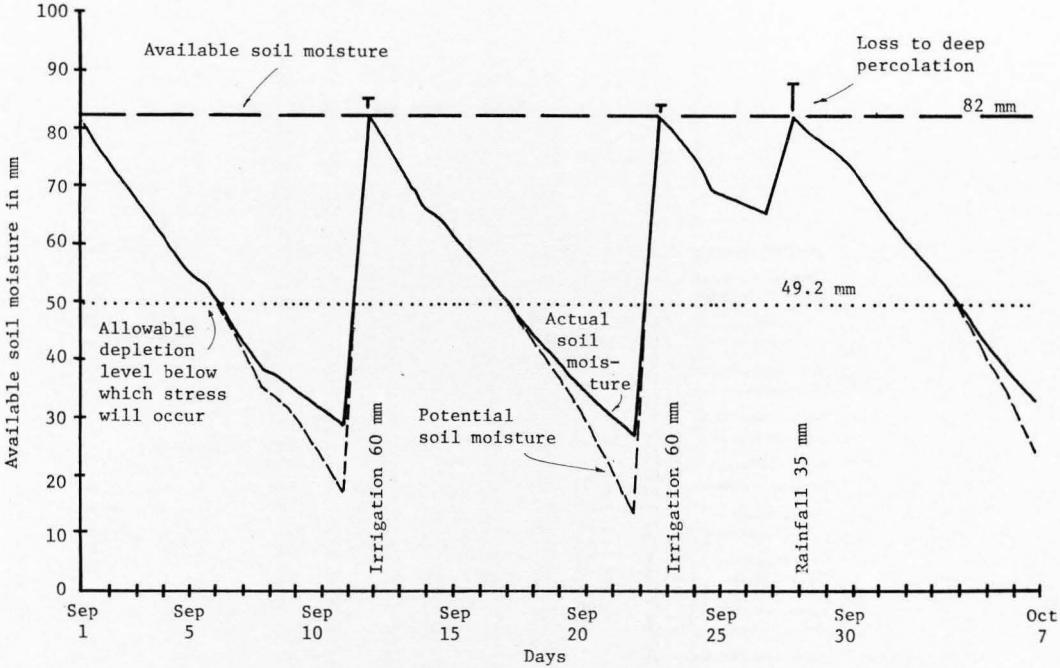

Figure 28. Available soil moisture in Field No. 10 for the period September 1 to October 7, 1973 showing effects of limiting soil moisture.

Table 10. Showing how the next irrigation date is determined in a Triangle PE1 soil

Field No. 6 Date	Crop[1] coeff.	Irrigation prediction portion: Class "A" pan evap.	Potential evapo-trans.	Actual evapo-trans.	Accum-ratio ET_a/ET_p	Avail. soil moisture
Aug 23	1.0	4.55	-	-	-	-
24	1.0	4.58	4.58	4.58	1.00	79.42[2]
25	1.0	4.62	4.62	4.62	1.00	74.79
26	1.0	4.66	4.66	4.66	1.00	70.13
27	1.0	4.70	4.70	4.70	1.00	65.43
28	1.0	4.74	4.74	4.74	1.00	-

[1]The irrigation coefficient is equal to 1.0.
[2]The value of expected soil moisture to first day after update on Aug 23.

ratio of actual evapotranspiration to potential evapotranspiration. Over the four cycles of irrigation, this ratio is equal to 0.86 which closely approximates the selected irrigation management coefficient of 0.85 for this period.

Figure 26 shows data for a sandy soil of the Triangle P3 category. The plot represents the soil moisture curve of Field 8 with 53 mm of total available moisture of which 34.5 mm (65 percent) is readily available. The irrigation coefficient of 0.85 is effective because the level of irrigation at 45 mm allows for the predicted accumulated daily potential and actual evapotranspiration values to computed below the allowable depletion level. This is similar to the relationship shown in Figure 25 and Table 11 for Field 7. Figure 26 shows the curve of actual soil moisture rapidly diverging from the potential soil moisture curve due to the soil moisture stress function responding to the approach of both curves to wilting point.

Table 11. Listing of actual available soil moisture in Field 7 (Triangle PE1 sandy clay loam), from August 5, 1973, to September 13, 1975

Field No. 7 Date	Potential evapotrans. (mm)	Actual evapotrans.	Accum. ET_a/ET_p	Available soil moisture
Aug 5	4.89	4.13		69.00
6	6.10	6.10	1.0	62.90
7	6.00	6.00	1.0	56.90
8	5.20	5.20	1.0	51.70
9	6.10	6.10	1.0	45.60
10	7.70	7.70	1.0	37.90
11	1.80	1.80	1.0	36.20
12	4.00	3.73	0.99	32.47
13	4.80	3.85	0.97	28.62
15	4.80	2.74	0.89	21.76
16	4.40	2.21	0.86	64.54
17	6.30	6.30	1.00	62.84
18	2.80	2.80	1.00	60.04
19	3.80	3.80	1.00	56.24
20	5.50	5.50	1.00	50.74
21	6.50	5.60	1.00	44.24
22	5.60	5.60	1.00	38.64
23	4.60	4.54	1.00	34.10
24	4.50	3.86	0.98	30.24
25	5.20	3.77	0.96	26.47
26	4.40	2.81	0.93	69.00
27	4.90	4.90	1.00	64.10
28	7.40	7.40	1.00	56.70
29	8.30	8.30	1.00	48.40
30	7.00	7.00	1.00	41.40
31	7.60	7.45	1.00	33.95
Sep 1	6.10	4.92	0.97	29.03
2	6.80	4.38	0.92	24.65
3	6.60	3.45	0.87	66.20
4	6.20	6.20	1.00	60.00
5	6.60	6.60	1.00	53.40
6	4.40	4.40	1.00	49.00
7	7.80	7.80	1.00	41.20
8	8.60	8.13	0.99	33.07
9	3.90	3.30	0.97	29.77
10	6.20	4.24	0.93	25.54
11	7.50	3.92	0.88	21.62
12	9.40	3.33	0.80	63.29
13	6.80	6.80	1.00	56.49
Period total	228.60	197.55	0.86	

The deep clay, Chisumbanje Basalt, soils are represented by Field 9 as illustrated in Figure 27. When the level of irrigation at 60 mm is less than the no stress allowable depletion of 81.12 mm, the prediction portion of the program determines when the next irrigation is due and maintains the soil moisture balance between total available and the allowable depletion level.

The shallow Chisumbanje Basalt clays are represented by Field 10 in Figure 28. The irrigation level of 60 mm exceeds the allowable depletion level and this ensures that the crop soil moisture curve enters the stress period determined by low soil moisture. The effects of limiting soil moisture and subsequent decreased evapotranspiration results in the divergence of the actual available soil moisture from the potential available soil moisture curve. This divergence is less than either the sandy clay loam soils or the sandy soils of Fields 7 and 8, and is due to the proportionally higher reservoir of soil water still available for crop use below the allowable depletion level. The irrigation coefficient value of 0.85 operated effectively due to the high irrigation level.

Evaluation of moisture losses

As described in the procedural section, the program differentiates moisture losses due to either irrigation or rainfall. On the assumption that all moisture applied enters the soil, the loss of moisture from the soil moisture system is attributed to deep percolation. Table 12 shows the moisture losses, for the same period in time, of Fields 6 and 7.

Field No. 6 on February 3 received 45 mm of irrigation and 1.1 mm of effective rainfall. Total moisture losses on this day from the root-zone amounted to 4.2 mm which the program, by the technique described in procedural sections breaks down into 1.1 mm due to rainfall and 3.1 mm due to over irrigation.

Field No. 7 on February 4 received only 45 mm of irrigation. In this case, the moisture loss of 1.64 mm can be attributed entirely to over irrigation. Between February 7 and 14, both fields received excess amounts of rainfall and these losses are all attributed to rainfall.

The summation of moisture losses, for the season to date, are printed with each update period printout. Table 13 is reproduced from the last update printout as on April 30, 1974.

The normal expected mean seasonal rainfall is 412 mm. A particularly high rainfall year was chosen for this study, with actual rainfall from September 1, 1973 to April 30, 1974 amounting to 919 mm. The effective rainfall, by equation [26], amounted to 689 mm which would indicate approximately 75 percent effectiveness. The high values attributed to rainfall losses, Table 13, are difficult to control during periods of considerable rainfall. This can be seen from Table 12 for Fields 6 and 7 during the period from February 7 to February 15, 1974. Rain fell on the fields when at or near field capacity leading to theoretical moisture losses due to deep percolation.

Significance of irrigation losses

Considerable significance, from an irrigation management standpoint, can be placed on moisture losses due to over irrigation.

Table 12. Distribution of moisture losses to deep percolation for Fields 6 and 7 between February 2, 1974 and February 17, 1974

	Field No. 6					Field No. 7				
	Actual ET (mm)	Actual soil moisture (mm)	Effective rainfall (mm)	Irrigation (mm)	Moisture loss (mm)	Actual ET (mm)	Actual soil moisture (mm)	Effective rainfall (mm)	Irrigation (mm)	Moisture loss (mm)
Feb 2	-	72.30								
3	4.20	110.00	1.10	45.0	4.20	-	29.65	-	-	-
4	5.80	104.20	-	-	-	4.01	69.00	-	45.0	1.64
5	4.50	99.70	-	-	-	4.50	64.50	-	-	-
6	6.50	93.20	-	-	-	6.50	58.00	-	-	-
7	5.90	88.30	1.00	-	-	5.90	53.10	1.00	-	-
8	6.40	104.56	22.66	-	-	6.40	69.00	22.66	-	0.36
9	3.10	110.00	10.00	-	1.46	3.10	69.00	10.00	-	6.90
10	2.80	108.40	1.20	-	-	2.80	67.40	1.20	-	-
11	2.10	106.40	0.10	-	-	2.10	65.40	0.10	-	-
12	5.10	101.30	-	-	-	5.10	60.30	-	-	-
13	0.90	110.00	20.49	-	10.89	0.90	69.00	20.49	-	10.89
14	2.80	110.00	10.90	-	8.10	2.80	69.00	10.90	-	8.10
15	3.10	107.00	0.10	-	-	3.10	66.00	0.10	-	-
16	5.90	101.10	-	-	-	5.90	60.10	-	-	-
17	5.80	95.30	-	-	-	5.80	54.30	-	-	-

Table 13. Accumulated moisture losses due to excess rain or irrigation from update printout of April 30, 1974

Field No.	Rainfall losses (mm)	Irrigation losses (mm)	Days since last harvest of beginning of growth
1	135.1	13.2	119
2	142.9	93.8	119
3	158.0	24.4	107
4	117.5	0.8	99
5	144.8	35.0	92
6	323.8	51.0	365
7	372.5	161.3	365
8	354.8	127.2	353
9	266.6	16.9	345
10	292.6	259.6	338
11	324.4	66.7	242
12	342.5	58.4	242
13	356.9	139.4	230
14	241.9	18.5	222
15	289.5	163.0	215

The lowest losses in irrigation were on the deep clays in Fields 4, 9, and 14 (Table 14). The irrigation level of 60 mm was considerably lower than the management allowed depletion level of 87.2 mm. The plot of available soil moisture in Figure 27 illustrates this effect in Field 9.

The highest losses occurred in those fields where irrigation exceeded the desired amount, in Fields 3, 5, 8, 10, 13, and 15. The plot of soil moisture in Fields 8 and 10 in Figures 26 and 28, respectively shows small excesses of moisture indicated by the small projection above the level of total available moisture.

Effectiveness of irrigation control

Another value in the update printout (Appendix C), labeled accumulated moisture deficit, gives an indication of how effective

Table 14. Accumulated excess depletion ($ET_p - ET_a$), due to limiting soil moisture, on April 30, 1974

Field	Days since harvest	Excess depletion at start of growth	Accumulated ET_p-ET_a since start of growth	ET_a/ET_p to date
1	119	42.9	13.5	0.96
2	119	17.25	10.15	0.96
3	107	10.55	18.85	0.92
4	99	0.0	0.0	1.00
5	92	18.04	12.96	0.95
6	365	22.00	3.40	1.00
7	365	20.70	85.80	0.91
8	353	10.55	166.15	0.85
9	345	27.00	0.50	1.00
10	338	16.40	105.20	0.89
11	242	22.00	4.10	0.99
12	242	20.70	47.10	0.93
13	230	10.55	58.35	0.90
14	222	27.00	1.30	0.99
15	215	16.40	58.40	0.89

the variations in irrigation level and soil moisture have been in maintaining the desired irrigation control on the plant-soil-moisture status.

The irrigation coefficient controls the degree of stress imposed on the crop. This is reflected in the ratio between accumulated potential evapotranspiration, ET_p, and actual evapotranspiration, ET_a.

Perfect irrigation control over the entire season of the crop would reflect the combination of the irrigation coefficients imposed for the three growth periods, and this value would vary depending on start of growth, length of crop cycle, and climate factors.

Table 14 shows the level of depletion in excess of allowable depletion at start of growth, and the accumulated daily difference between potential evapotranspiration and actual evapotranspiration.

Limiting (low) levels of irrigation, which were less than the allowable depletion, had the effect of not allowing the prediction of the next irrigation, on the basis of the irrigation coefficient, to occur. This effect is discussed in the procedural section and is shown graphically for Field 6 in Figure 24.

When the depth of irrigation exceeds the allowable depletion level, the irrigation coefficient becomes effective in predicting the next irrigation. This effect was well demonstrated in Fields 7, 8, and 10 (Figures 22, 23, and 25).

Fields 6 and 7 have completed a full season of growth with Fields 8, 9, and 10 near completion (Table 13). The ET_a/ET_p ratios are an indication of the overall seasonal effects of irrigation management.

The ET_a/ET_p values of Fields 6 and 9 are equal to 1.0 indicating that the irrigation control was limited by low levels of irrigation which would not allow depletion below that required to refill the soil moisture reservoir.

The irrigation coefficient was effective in Fields 7, 8, and 10, which can be seen in the seasonal ET_a/ET_p ratio of 0.91, 0.85, and 0.89. In these fields irrigation exceeded allowable depletion. This excess ensured that the desired limiting effects of soil moisture on daily actual evapotranspiration were accumulated until the ET_a/ET_p ratio, the irrigation coefficient of 0.85 was reached.

The irrigation coefficient of 0.60 was only partially effective in any of the fields during the drying off period. The prediction process requires for the total soil profile to be brought to field capacity and if the irrigation level is not sufficiently deep to meet this requirement at the 0.60 irrigation coefficient level, the next irrigation is called for on the basis of the limiting depth of irrigation. The irrigation level on Fields 7, 8, and 10 were all insufficient and the accumulated ET_a/ET_p ratio of 0.60 was never obtained.

CONCLUSIONS

Correlation of pan evaporation with equations of potential evapotranspiration

The Penman and Christiansen-Hargreaves equations all correlated well with actual Class "A" pan evaporation values. The Jensen-Haise equations showed a markedly lower correlation which can be attributed to the semi-arid climate-specific characteristics of the equation.

All the equations evaluated underestimated pan evaporation. The statistical analysis of the regression lines indicates significant differences at the 95 percent level between years. However, the plot of confidence limits about the regression lines shows that for the range of expected seasonal pan evaporation values, the magnitude of the variation could be acceptable as an alternate measure of pan evaporation for irrigation control.

The effects of the two solar radiation values used in the equations is reflected in the higher correlations obtained with measured, Gunn-Bellani, radiation. This effect was not large and resulted in only a small R^2 increase of measured over calculated radiation forms of the equations. The lower values of calculated radiation resulted in a decrease in slope of the pan evaporation prediction (regression) line.

The effect of differing levels of albedo on the Penman equations was observed with a proportional decrease in the slope of the pan evaporation prediction line due to the decrease in albedo values of a free surface to that of an actively growing green crop.

Of all the equations evaluated, it would appear that both the Penman and Christiansen-Hargreaves equations would adequately predict pan evaporation. The equation which showed the highest correlation with Class "A" pan evaporation and also resulted in a slope which approached 1.0 was the Christiansen-Hargreaves formula which used measured radiation as the significant climatic input.

Irrigation schedule for sugarcane

The versatility of the scheduling program was demonstrated on five soil moisture variations (three soil type categories) under both limiting and adequate depths of irrigation.

The program demonstrates that for sugarcane the depth of irrigation applied is an important irrigation control factor. When the level of irrigation applied did not exceed the allowable depletion, the irrigation management coefficients were not effective, and crop water use was maintained at the potential rate. Irrigation levels in excess of allowable depletion allowed for soil moisture depletion into the moisture stress region until the ET_a/ET_p ratio reached the desired 0.85 value. The irrigation coefficient of 0.60 for drying off was never attained due to the limiting effect of the levels of applied irrigation. This would indicate the need for some flexibility in varying the depth of irrigation during the crop growth cycle.

The sine functions developed for estimating the crop and irrigation coefficients should reflect crop variety differences and annual variations in climate. The fluidity shown by these functions in the program ignores these factors and is a major weakness of the irrigation management approach.

The assumption that homogeneous soil moisture conditions exist, which are easily defined, does not in reality occur in the field. The effective implementation of this scheduling program will depend on studies which will clearly define the soil moisture characteristics of the Rhodesian Lowveld soils with regard to the irrigation of sugarcane.

The program indicated some sensitivity to determining moisture losses. This estimate would have considerable influence in irrigation management evaluation, but it is dependent upon accurate knowledge of the specific soil-plant-atmosphere moisture interaction.

It can be concluded that the irrigation scheduling program has demonstrated a technique of effective irrigation control for sugarcane which could be a significant step towards better irrigation water use and maximized sugar yields in irrigated sugarcane.

Future research needs

This study has illuminated many areas of interest which would require further investigation in order to add more precision to the irrigation scheduling program for sugarcane. These are,

1. The availability of soil moisture for plant growth, in particular, the following aspects:

    a. Differential soil moisture extraction patterns related to root distribution and age of crop.

    b. Lateral and upward movement of soil moisture.

    c. The salinity levels of soil water and its effect on the uptake of moisture by sugarcane.

2. The variable rates of transpiration of the crop which are determined by the interrelation of the depletion level of soil moisture and the evaporative demands of the atmosphere.

3. The modification of the crop and irrigation coefficents in terms of plant variety, cropping practice together with some measure of accumulated radiation or growing degree days which would reflect seasonal differences more accurately.

4. The efficiency and method of irrigation and its effect on the sensitivity of the program to control the soil-plant-moisture regime for optimum crop water use.

The implementation of many of the suggestions requires sophisticated instrumentation. It is felt, however, that in order to optimize crop water use for maximum crop productivity, the expenditure involved will be significantly offset by an improved knowledge of crop water use and better irrigation control.

LITERATURE CITED

Agricultural Research Service. 1975. Irrigation scheduling services. M. E. Jensen (Ed.). U.S.D.A., Kimberly, Idaho.

American Society of Agronomy. 1967. Irrigation of agricultural lands. R. M. Hagan, R. M. Haise, and T. W. Edminster (Eds.). Mono. No. 11., Amer. Soc. Agron., Madison, Wisconsin. 1180 pp.

Buras, N. F., D. Nir, and E. Alpervits. 1973. Planning and updating farm irrigation scheduled. J. Irrig. and Drain. Div., ASCE, 99:43-51.

Campbell, R. B. 1967. Sugarcane. In R. M. Hagan, H. R. Haise, and T. W. Edminster (Eds.). Irrigation of agricultural lands. Mono. No. 11, Amer. Soc. Agron., Madison, Wisconsin. pp. 649-653.

Chang, J. H. 1961. Microclimate of sugarcane. Hawaiian Planters' Rec. 56:195-225.

Christiansen, J. E. 1972. Irrigation requirements in Latin American countries. ITCC Review. Vol. 1 & 2, pp. 40-50.

Doorenbos, J, and W. P. Pruitt. 1975. Crop water requirements. FAO, Rome. 179 pp.

Duffie, J. A., and W. A. Beckman. 1974. Solar energy thermal processes. First Edition. John Wiley and Sons, New York. 386 pp.

Franzoy, C. E. 1969. Predicting irrigation from climatic data and soil parameters. Amer. Soc. Agr. Eng., Winter Meeting.

Franzoy, C. E., and E. L. Tankersley. 1970. Predicting irrigations for climatic data and soil parameters. Trans. Amer. Soc. Agr. Eng. 13:814-816.

Gosnell, J. M. 1970. Optimum irrigation levels for cane under burn and trashed conditions. Proc. of S. Afr. Sugar Tech. Assoc. 44:121-127.

Gosnell, J. M., and J. E. Lonsdale. 1974. Some effects of drying off before harvest on cane yield and quality. Proc. 15th Congr. Int. Soc. of Sugar Cane Tech., Durban, South Africa.

Haise, H. R., and R. M. Hagan. 1967. Soil, plant, and evaporative measurements as criteria for scheduling irrigation. In R. M. Hagan, H. R. Haise, and T. W. Edminster (Eds.). Mono. No. 11, Amer. Soc. of Agron., Madison, Wisconsin. pp. 577-604.

Hillel, D. 1971. Soil and water: Physical principles and processes. Academic Press, New York. 288 pp.

Idso, S. B., and R. D. Jackson. 1969. Thermal radiation from the atmosphere. J. Geophys Res. 74:5397-5403.

Jensen, M. E. 1969. Scheduling irrigation with computers. J. of Soil and Water Cons. 24:193-195.

Jensen, M. E., D. C. N. Robb, and C. E. Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. J. Irrig. and Drain. Div., Amer. Soc. Civ. Eng. 96:25-28.

Jensen, M. E., J. L. Wright, and B. J. Pratt. 1971. Estimating soil moisture depletion from climate, crop, and soil data. Trans. Am. Soc. Agric. Eng. 14:954-959.

Jensen, M. E. 1972. Programming irrigation for greater efficiency. In D. Hillel (Ed.). Optimizing the soil physical environment toward greater crop yields. Academic Press. pp. 133-161.

Jensen, M. E. 1973. Consumptive use of water and irrigation water requirements. Amer. Soc. Civ. Eng., New York. 215 pp.

Jensen, M. E. 1976. Private communication.

Lonsdale, J. 1976. Private communication.

Metelerkamp, H. R. R. 1968. The use of evaporation pans for irrigation control. Rhod. Agric. J. 65:37-51.

Middlebrooks, E. J. 1976. Statistical calculations. Ann Arbor Science, Michigan. 120 pp.

Neter, J., and W. Wasserman. 1974. Applied linear statistical models. Irwin, Illinois. 842 pp.

Parmele, L. H., and J. L. McGuinnes. 1974. Comparisons of measured and estimated daily potential evapotranspiration in humid areas. J. of Hydrology 22:239-251.

Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc., London A193:120-145.

Penman, H. L. 1961. Weather, plant, and soil factors in hydrology. Weather 16:207-219.

Penman, H. L. 1963. Vegetation and hydrology. Technical Comm., No. 53, Commonwealth Bureau of Soils, Harpenden, England. 125 pp.

Pruitt, W. W. 1966. Empirical method of estimating evapotranspiration using primarily evaporation pans. In Evaporation and its role in water resources management. Amer. Soc. Agric. Eng., St. Joseph, Michigan. pp. 56-61.

Rhodesia Sugar Association Experiment Station. 1974. Unpublished review of irrigation trials.

Robinson, F. E. 1963. Soil moisture tension, sugarcane stalk elongation and irrigation interval control. Agron. J. 55:481-484.

Robinson, N. 1966. Solar radiation. Elsevier, New York. 347 pp.

Rose, C. W. 1966. Agricultural physics. Pergamon, New York 226 pp.

Sellars, W. K. 1974. Physical climatology. 5th Edition. University of Chicago, Chicago. 272 pp.

Stanhill, G., and Y. Vaadia. 1967. Factors affecting plant response to soil water. In R. M. Hagan, R. H. Haise, T. M. Edminster (Eds.). Irrigation of agricultural lands. Mono. No. 11. Amer. Soc. Agron., Madison, Wisconsin. pp. 446-453.

Stephens, J. L., 1965. Estimating evaporation from insolation. J. Hydr. Div., Amer. Soc. Civ. Eng. 91:171-182.

Tanner, C. B. 1967. Measurement of evaporation. In R. M. Hagan, H. R. Haise, and T. W. Edminster (Eds.). Irrigation of agricultural lands. Mono. No. 11. Amer. Soc. Agron., Madison, Wisconsin. pp. 534-555.

Tanner, C. B. 1968. Evaporation of water from plants and soil. In T. T. Koslowski (Ed.). Water deficits and plant growth. Vol. 1. Academic Press, New York. pp. 73-106.

Taylor, S. A., and G. L. Ashcroft. 1972. Physical edaphology. W. H. Freeman and Company. 533 pp.

Thompson, G. D., C. H. O. Pearson, and T. G. Cleasby. 1963. Estimation of the water requirements of sugarcane in Natal. Proc. S. Afr. Sugarcane Tech. Assoc. pp. 1-8.

Thompson, G. D., J. M. Gosnell, and P. J. M. de Robillard. 1967. Responses of sugarcane to supplementary irrigation on two soils in Natal. Exptl. Agric. Vol. 3.

Thompson, G. D., and Boyce, J. P. 1971. Comparisons of measured evapotranspiration of sugarcane from large and small lysimeters. Proc. S. Afr. Sugarcane Tech. Assoc. pp. 1-8.

Thompson, G. D., and J. P. Boyce. 1972. Estimating water use by sugar cane from meteorological and crop parameters. Proc. Int. Soc. Sugarcane Tech. 14th Congress. pp. 813-826.

Toit, A. A. du. 1968. The soils of the sugar-producing areas in the southeastern Lowveld of Rhodesia. Rhod. Agric. J. 65:82-86.

Wilson, G. J., and H. R. R. Metelerkamp. 1974. An estimate of evapotranspiration and net monthly and seasonal irrigation requirements at Chisumbanje. Rhod. Agric. J. 71:65-70.

Wright, J. L., and M. E. Jensen. 1972. Peak water requirements of crops in Southern Idaho. J. Irrig. Drain. Div., Amer. Soc. Civ. Eng. 96:193-201.

APPENDIXES

Appendix A

A Method of Calculation for Daily Extraterrestrial and Solar Radiation on a Horizontal Surface

Extraterrestrial and solar radiation estimates

The geometric relationship between a plane and the incoming beam solar radiation can be described in terms of several angles.

ϕ = latitude (north positive)

σ = declination (the angular position of the sun at solar noon with respect to the plane of the equator, north positive)

s = the angle between the horizontal and the incident plane.

γ = the surface azimuth angle, that is, the deviation of the normal to the surface from the local meridian. Zero point being due south, east positive and west negative.

ω = hour angle, solar noon being zero and each hour equaling 15 degrees with mornings positive and afternoons negative (e.g. $\omega = +15$ for 11:00 a.m. and $\omega = -37.5$ for 14:30 p.m.)

θ = the angle of incidence of beam radiation, the angle being measured between the beam and the normal to the incident plane.

The declination, σ, can be found from the approximate equation,

$$\sigma = 23.45 \text{ Sin } [360 \frac{(284 + n)}{365}] \qquad [A1]$$

where n is the Julian day of the year.

In this study, radiation data was required for 24-hour periods on a horizontal surface and therefore the variable, s, for defining the variation from horizontal of the incident plane and γ, the azimuth angle relative to the time meridian, are excluded from determination of the radiation values.

The calculation of extraterrestrial radiation on a horizontal surface for any day of the year at any latitude can be calculated from:

$$R_A = \frac{24}{\pi} I_{sc} \left([1 + 0.033 \cos (\frac{360n}{365})][\cos \phi \cos \sigma \sin \omega_s + \frac{2\pi \omega_s}{360} \sin \phi \sin \sigma]\right) \qquad [A2]$$

where σ is calculated from equation [A1].

Daylength is calculated from

$$T_d = \frac{2}{15} \cos^{-1} (-\tan \phi \tan \sigma) \qquad [A3]$$

where T_d is daylight from which the sunrise hour angle, ω_s, can be calculated by

$$\omega_s = T_d (7.5) \qquad [A4]$$

In addition to the calculation of extraterrestrial radiation, data on hours of, or percent possible sunshine coupled with coefficients of geographic location leads to the calculation of solar radiation at the surface by the following equation:

$$R_S = R_A (a + b \frac{n}{N}) \qquad [A5]$$

where n is the hours of actual sunshine and N is the maximum possible hours of sunshine, equivalent to daylength, if no obstructing topographical features limit day length at the point of measured solar radiation. Variations due to climatic variables are represented by the constants a and b. Duffie and Beckman (1974) present a table of climatic constants for use in equation [A5].

Appendix B

Irrigation Scheduling Program and Sample Input Deck

```
$ SET AUTOBIND
$ BIND PL360 FROM UTILITY/=
C ***********************                    ******************************
C ***********************        SUGAR       ******************************
C
C       THIS PROGRAM UPDATES THE SOIL WATER BALANCE AND PREDICTS THE DATE
C                 OF THE NEXT IRRIGATION FOR SUGARCANE
C
C ****************************************************************************
C ****************************************************************************
C
C
FILE  1=SCHEDULE,UNIT=DISKPACK,RECORD=5490,BUFFER=1,AREA=1*1000,SAVE=99


      REAL MTTH,MTMC,MTHD,NDCOV,NMCOV,NMCLI,NDCLI,NDIRP,MDIRP,IDIR,MTIR,
     $NDNHR,NMMHR
      INTEGER YRR,HRVM,HRVD,YR,DAY,YSTOR
      DIMENSION A(1045),XD(12),YD(9),MD(12)
      COMMON YR,DAY,YSTOR,ND,IDYS,MTTH,ETPSX,ETP47,ETPS7,ETPF14,ETPF7,
     $ETPTC,MONTH,J,I,NSAVE,NEND,IFKP,ATR,JYR
      COMMON /A/ MTHA(12),MTHB(12),MTMC(12),MTHD(12),PRCP(366),
     $RN(366),ETAC(15,366),ETAM(15,366),AVMS(15,366),EVAPE(36
     $6),ETAE(15,366),FTAE(15,366),ADPL(15),FSLOP(15),NDHRV(15),FSLTX(1
     $5),ETASS(15),ADRIP(15),AVMSC(15,366),ODPL(15),DKCC(15),
     $AVMSX(15,366),FAVMSX(15),AMMSX(15),DKA(15)
      COMMON /B/ FDIRI(15),NMHRV(15),NNHRV(15),TAVE(366),RS(366),TMIN(36
     $6),TMAX(366),WND(366),DRRI(15,366),NDCOV(15),NMCOV(15),EVAPC(3
     $66),NDCLI(366),NMCLI(366),NDIRP(15),MDIRP(15),RH(366),CKCC(15,
     $366),OVER(15,366),FAVMS(15),SDRIR(15),NIRI(15),ETAES(15),
     $ETAES(15),IDIR(15),MTIR(15),FTAM(15),FHECT(15),SETAM(15)
      COMMON /C/ AMMS(15),AMMSC(15),WARN(15,366),DTAMC(15),DMAMX(15),
     $OVERF(15),OVERI(15),NEPDY(15),DEPSM(15),CKCC(15),NDNHR(15),NMMHR(1
     $5),DEPSS(15,366),NNAY(366),SRN(15),SPRCP(15),AAMS(366)
      DATA(MTHA(N),N=1,12)/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHB(N),N=1,12)/31,29,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHC(N),N=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      DATA(MTHD(N),N=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      DATA A/1045*'    '/
      DATA MD/12*'    '/
      DATA XD/12*'    '/
      DATA YD/9*'    '/
C
C       ALL DISKFILE ARRAYS CAN BE SET TO ZERO
C****************************************************************************
      READ(5,841)NARRAY

  841 FORMAT(I1)
      IF(NARRAY.EQ.1)GO TO 847
C

C       SEASONAL ACCUMULATED DATA AND VARIOUS FIELD CONSTANTS ARE READ
C       FROM DISKFILE STORAGE FOR EXECUTION OF THE WATER BALANCE UPDATE
C       PERIOD.
C****************************************************************************
      READ (1)AVMS
      READ (1)CKC
      READ (1)ETA
      READ (1)ETAM
      READ (1)ETAE
      READ (1)ETAES
      READ (1)OVER
      READ (1)DEPSS
      READ (1)AVMSE
      READ (1)DRRI
      READ (1)WARN
      READ (1)PRCP,RN,EVAP,EVAPE,SRN,SPRCP,SDRIR,SETAM,NSAVE,IFKP,FSLOP,
     $NDHRV,FSLTX,ETASS,ADRIR,OVERP,OVERI,DEPSM,NDNHR,NMMHR,FDIRI,AMMS,
     $NMHRV,NNHRV,NIRI,IDIR,MTIR,FTAM,FHECT,NDCOV,NMCOV,NDCLI,NMCLI,
     $NDIRP,MDIRP,FAVMS,NNAY,ADPL,NEPDY
      READ (1)AVMSX
      READ (1)FAVMSX,DKC,ODPL
      READ (1)AMMSX
      READ (1,END=847)DKA
  847 REWIND 1
      HD(1)='SOIL M'
      HD(4)='DISTUR'
      HD(5)='E CONT'
      HD(6)='ENT 75'
      HD(7)=' JULIA'
      HD(8)='N DAY '
      YD(3)='AVAILA'
      YD(4)='BLE MO'
      YD(5)='ISTURE'
      YD(6)=' IN MM'
      XD(4)='STUDY '
      XD(5)='PERIOD'
      XD(6)=' IN DA'
      XD(7)='YS    '
      MM=0
      DO 329 K=1,15
C
C       READ: THE LISTING OF RELEVANT DATA AND THE PLOT OF AVAILABLE SOIL
C        MOISTURE IS AN OPTIONAL PART OF THE PROGRAM
C       FILLER CARD MUST HAVE 1111 IN COLUMNS 1234
C****************************************************************************
      READ(5,330,ERR=155)IIF,JFN,LIM
  330 FORMAT(3I4)
      IF(IIF.EQ.1111)GO TO 11
      MM=MM+1
      I=IIF
      WRITE(6,331)IIF

  331 FORMAT('1',T20,'PERIOD DATA FOR FIELD NUMBER ',I4)
      WRITE(6,332)
  332 FORMAT(' ',T20,34('-'),////)
      WRITE(6,333)
  333 FORMAT(' ',T4,'JDAY   CKC    EVAP   ETA    AVMSX  ETAM   AVMS   EV
     $APE  ETAE   ETAFP  AVMSE  WARN   DEPSS   RN    PRCP   DRRI   OVER
     $',/)
      DO 334 K=1,366

      NNAY(K)=0
      AAMS(K)=0
  334 CONTINUE
      N=0
      IF(JFN.LT.LI4)GO TO 335
```

```
      GO TO 341
  335 JST=366-(LIM-JFN)
        JJT=JST+366
      DO 337 J=JST,366
      WRITE(6,344)J,CKC(I,J),EVAP(J),ETA(I,J),AVMSX(I,J),ETAM(I,J),AVMS(
     $I,J),EVAPE(J),ETAE(I,J),ETAEM(I,J),AVMSE(I,J),WARN(I,J),DEPSS(I,J)
     $,RN(J),PRCP(J),DFRI(I,J),OVER(I,J)
  344 FORMAT(' ',I5,16(F7.2))
      N=N+1
      NNAY(N)=N
      AAMS(N)=AVMS(I,J)
  337 CONTINUE
      DO 329 J=1,JFN
      WRITE(6,346)J,CKC(I,J),EVAP(J),ETA(I,J),AVMSX(I,J),ETAM(I,J),AVMS(
     $I,J),EVAPE(J),ETAE(I,J),ETAEM(I,J),AVMSE(I,J),WARN(I,J),DEPSS(I,J)
     $,RN(J),PRCP(J),DFRI(I,J),OVER(I,J)
  346 FORMAT(' ',I5,16(F7.2))
      N=N+1
      NNAY(N)=N
      AAMS(N)=AVMS(I,J)
  339 CONTINUE
      CALL PL360(LIM,A,NNAY,0.0,LIM,XO,AAMS,0.0,225.0,YO,HO,92)
      GO TO 349
  341 JST=JFN-LIM
      DO 342 J=JST,JFN
      WRITE(6,338)J,CKC(I,J),EVAP(J),ETA(I,J),AVMSX(I,J),ETAM(I,J),AVMS(
     $I,J),EVAPE(J),ETAE(I,J),ETAEM(I,J),AVMSE(I,J),WARN(I,J),DEPSS(I,J)
     $,RN(J),PRCP(J),DFRI(I,J),OVER(I,J)
  338 FORMAT(' ',I5,16(F7.2))
      N=N+1
      NNAY(N)=N
      AAMS(N)=AVMS(I,J)
  342 CONTINUE
      CALL PL360(LIM,A,NNAY,0.0,LIM,XO,AAMS,0.0,225.0,YO,HO,92)
  349 WRITE(6,351)SETAM(I)
  351 FORMAT(*1*,T20,*TOTAL EVAPOTRANSPIRATION NETT     =*,F8.2,* MM*,/)
      WRITE(6,359)SIASS(I)
  359 FORMAT(' ',T20,*TOTAL EVAPOTRANSPIRATION GROSS    =*,F8.2,* MM*,/)
      WRITE(6,352)SRN(I)
  352 FORMAT(' ',T20,*TOTAL GROSS RAINFALL              =*,F8.2,* MM*,/)
      WRITE(6,356)SPRCP(I)
  356 FORMAT(' ',T20,*ADJUSTED RAIN "PRECIPITATION"     =*,F8.2,* MM*,/)
      WRITE(6,358)SDRIR(I)
  358 FORMAT(' ',T20,*TOTAL IRRIGATION APPLIED          =*,F8.2,* MM*,/)
      WRITE(6,712)DEPSM(I)
  712 FORMAT(' ',T20,*TOTAL EXCESS DEPLETION            =*,F8.2,* MM*,/)
      WRITE(6,713)NEPDY(I)
  713 FORMAT(' ',T20,*TOTAL EXCESS DAYS                 =*,I4,/)
  329 CONTINUE
      GO TO 500
C      READ: NSAVE GOES TO ZERO WHENEVER A RUN WITHOUT CLIMATE DATA IS
C      EXECUTED. THIS OPTION ALLOWS THE REINITIALISING OF NSAVE TO THE
C      LAST UPDATE PERIOD.
C      FILLER CARD MUST HAVE 555 IN COLUMNS 123
C*****************************************************************

   11 DO 12 I=1,2
      READ(5,15)ISAVE
   15 FORMAT(I3)
      IF(ISAVE.EQ.555)GO TO 21
      NSAVE=ISAVE
   12 CONTINUE
C      READ: THIS IS AN OPTION TO CHANGE THE DATE OF THE NEXT HARVEST
C      FILLER CARD MUST HAVE 2222 IN COLUMNS 1234
C*****************************************************************
   21 DO 605 K=1,13
      READ(5,600)IFC,YFC,MFC,NDC
  600 FORMAT(4(I4))
      IF(IFC.EQ.2222)GO TO 606
      YR=YFC
      MONTH=MFC
      DAY=NDC
      CALL NDAY
      NNHRV(IFC)=KD
      CALL MONDAY
      NMHRV(IFC)=NTH
      NDNHR(IFC)=IDYS
  605 CONTINUE
C
C      READ: INDIVIDUAL FIELDS AT HARVEST HAVE ALL ARRAYS SET TO ZERO
C      WITH THIS OPTION.
C      FILLER CARD MUST HAVE 333 IN COLUMNS 123
C*****************************************************************
  606 DO 625 M=1,13
      READ(5,615)KF,JSS,JFF
  615 FORMAT(3(I3))
      IF(KF.EQ.333)GO TO 626
      I=KF
      DO 620 J=JSS,JFF
      OVER(I,J)=0
      DEPSS(I,J)=0
      DRRE(I,J)=0
      WARN(I,J)=0
      PRCP(J)=0
      RN(J)=0
      SRN(I)=0
      SPRCP(I)=0
      SDRIR(I)=0
      SETAM(I)=0
      SIASS(I)=0
      OVERP(I)=0
      OVERI(I)=0
      DEPSM(I)=0
      AMMS(I)=0
      AMMSX(I)=0
      NIRI(I)=0
      FAVMS(I)=0
      FAVMSX(I)=0
      NEPDY(I)=0
  620 CONTINUE
  625 CONTINUE
      GO TO 501
C
C      READ: ANY CORRECTION TO CURRENT FIELD SOIL MOISTURE AND
C      IRRIGATION VALUES IS EXECUTED WITH THIS OPTION.
C      FILLER CARD MUST HAVE 444 IN COLUMNS 123

C*****************************************************************
  626 DO 23 I=1,25
      READ(5,22)NF,NIRIC,FAVMSC,SDRIRC,OVERPC,OVERIC,DEPSMC
   22 FORMAT(I3,I3,5(F6.1))
      IF(NF.EQ.444)GO TO 24
```

```
      NIRI(NF)=NIRIC
      FAVMS(NF)=FAVMSC
      SDRIK(NF)=SDRIRC
      OVERF(NF)=OVERFC
      OVERI(NF)=OVERIC
      DEPSM(NF)=DEPSMC
      AMMS(NF)=FTA(NF)-FAVMSC
   23 CONTINUE
C
C       READ: THE INITIALISING OF FIELD CONSTANTS FOR NEW FIELD SEASON
C       ON THE DAY OF HARVEST OR WHEN GROWTH FIRST OCCURS AFTER PLANT-
C       ING.
C       FILLER CARD MUST HAVE 888 IN COLUMNS 123
C*****************************************************************
   24 KK=0
      DO 16 I=1,15
      READ(5,25,ERR=145)NUM,YRR,HRVM,HRVD,HECT,SLOP,TAM,POL,DIRI,SLTX,
     $SSTR
   25 FORMAT(I3,2X,I4,1X,I2,3X,I2,3X,F5.1,F5.1,F5.1,F5.2,F5.1,A6,F4.2)
      IF(NUM.EQ.888)GO TO 88
      IF=NUM
      KK=KK+1
      IF(MOD(YRR,4).EQ.0)GO TO 34
      YSTOR=1
      GO TO 35
   34 YSTOR=2
   35 FSLOP(IF)=SLOP
      OOPL(IF)=POL
      AOPL(IF)=TAM*POL
      FHECT(IF)=HECT
      NOHRV(IF)=HRVD
      FSLTX(IF)=SLTX
      FTAM(IF)=TAM
      FDIRI(IF)=DIRI
      NMHRV(IF)=HRVM
      YR=YRR
      MONTH=HRVM
      DAY=HRVD
      CALL NDAY
      NNHRV(IF)=ND
      CALL MONDAY
      NDNHR(IF)=IDYS
      NMMHR(IF)=MTH
      MCOV=NNHRV(IF)
      IF(IF.GT.IFKP)IFKP=IF
      AMMS(IF)=FTA(IF)*SSTR
      AMMSX(IF)=AMMS(IF)
      NCOV=0
      I=IF
      DO 28 J=MCOV,MCOV+150
      CALL CROPKC
      IF(CKC(I,J).GE.1.00)GO TO 29
      NCOV=NCOV+1
   28 CONTINUE
   29 NCCOV=NCOV+1+NNHRV(IF)

      ND=NCCOV
      IF(YSTOR.EQ.1)GO TO 45
      IF(NCCOV.GT.166)ND=NCCOV-366
      GO TO 48
   45 IF(NCCOV.GT.165)ND=NCCOV-365
   46 CALL MONDAY
      NDCOV(IF)=IDYS
      NMCOV(IF)=MTH
   16 CONTINUE
C
C       READ: CLIMATE DATA FOR UPDATE EXECUTION OF THE SOIL WATER
C       BALANCE. A VARIABLE NUMBER OF DAYS CAN BE ENTERED.
C       FILLER CARD MUST HAVE 9999 IN COLUMN 1234
C*****************************************************************
   88 JJ=0
      DO 89 J=1,20
      READ(5,105,ERR=148)XYR,MONTH,DAY,TMM,TNN,RAIN,RAD,RHUM,WIND,
     $TOBB,TWBB,DPT,SUNN,CLOUD,EPAN
  105 FORMAT(I4,I2,I2,F4.1,1X,F4.1,1X,F5.1,F4.0,1X,F3.0,2X,F3.1,2X,4(F4.
     $1,1X),F3.1,2X,F4.1)
      IF(XYR.EQ.9999)GO TO 65
      YR=XYR
      JJ=JJ+1
      CALL NDAY
      IF(ND.EQ.1)EPTO=0.00
      TAVE(ND)=(TMM+TNN)/2
      RS(ND)=RAD
      TMIN(ND)=TNN
      TMAX(ND)=TMM
      RN(ND)=RAIN
      EVAP(ND)=EPAN
      WND(ND)=WIND*1.609*24
      RH(ND)=RHUM
      IF(MOD(YR,4).EQ.0)GO TO 91
      YSTOR=1
      GO TO 93
   91 YSTOR=2
   93 CALL MONDAY
      NMCLI(ND)=MTH
      NDCLI(ND)=IDYS
   89 CONTINUE
   65 IF(JJ.EQ.0)GO TO 271
      NEND=ND
C
C       READ: IRRIGATION INPUT FOR UPDATE EXECUTION OF THE SOIL WATER
C       BALANCE. MORE THAN ONE IRRIGATION PER FIELD PER UPDATE PERIOD
C       CAN BE READ.
C       FILLER CARD MUST HAVE 777 IN COLUMN 123
C*****************************************************************
      II=0
      DO 70 M=1,20
      READ(5,66,ERR=152)NFI,NMI,NDI
   66 FORMAT(I3,2X,I2,3X,I2)
      IF(NFI.EQ.777)GO TO 128
      II=II+1
      MONTH=NMI
      DAY=NDI
      CALL NDAY
      DO 36 K=1,IFKP
      IF(NFI.NE.K)GO TO 36

      CALL MONDAY
      NDIRF(K)=IDYS
      MDIRF(K)=MTH
      DO 38 J=NSAVE+1,NEND
      IF(ND.EQ.J)DRRI(K,J)=1
```

```
   36 CONTINUE
   36 CONTINUE
   70 CONTINUE
C     THE FOLLOWING  FOUR DO LOOPS ARE IN THE PROGRAM TO INDICATE IF
C     AND WHERE ANY ERROR OCCURS ON THE READ INPUT CARDS
  145 KKK=KK+1
      WRITE(6,146)KKK
  146 FORMAT(' *,T20,'ERROR IN FIELD INPUT CARD NUMBER *,I2)
      GO TO 500
  148 JJJ=JJ+1
      WRITE(6,149)JJJ
  149 FORMAT(' *,T20,'ERROR IN CLIMATE INPUT CARD NUMBER *,I2)
      GO TO 500
  152 III=II+1
      WRITE(6,154)III
  154 FORMAT(' *,T20,'ERROR IN IRRIGATION INPUT CARD NUMBER *,I2)
      GO TO 500
  155 MMM=MM+1
      WRITE(6,156)MMM
  156 FORMAT(' *,T20,'ERROR IN ARRAY INPUT CARDS NUMBER *,I2)
      GO TO 500
C
C       THE PROGRAM NOW EXECUTES THE UPDATING OF THE ACTUAL SOIL
C        WATER BALANCE OVER THE UPDATE PERIOD.
C*****************************************************************
  128 DO 50 I=1,IFKP
      DO 66 J=NSAVE+1,NEND
      NK=0
      CALL CROPKC
      ETA(I,J)=EVAP(J)+CKC(I,J)
      ETASS(I)=ETASS(I)+ETA(I,J)
      ETAS=AMMS(I)-ETA(I,J)
      IF(EFTAM(I)-ETAS)/FTAM(I).LE.ODPL(I))GO TO 205
      NK=1
      EE=(ETAS/FTAM(I))*(1/(1-ODPL(I)))
      ETAM(I,J)=ETA(I,J)+EE
      GO TO 206
  205 ETAM(I,J)=ETA(I,J)
  206 SETAM(I)=SETAM(I)+ETAM(I,J)
      SRN(I)=SRN(I)+RN(J)
      IF(RN(J).LE.20.0)GO TO 140
      PRCP(J)=RN(J)*(0.375)+12.5
      GO TO 141
  140 PRCP(J)=RN(J)
  141 SPRCP(I)=SPRCP(I)+PRCP(J)
      IF(DIRI(I,J).NE.1.0)GO TO 207
      DIRI=FDIRI(I)
      GO TO 214
  207 DIRI=0
  214 IF(NK.NE.1)GO TO 213
      AVMSX(I,J)=AAMSX(I)-ETA(I,J)+PRCP(J)+DIRI
      IF(AVMSX(I,J).LT.C.0)AVMSX(I,J)=C.01
  213 AVMS(I,J)=AMMS(I)-ETAM(I,J)+PRCP(J)+DIRI
      IF(NK.EQ.1)GO TO 217
      AVMSX(I,J)=AVMS(I,J)

C
C       THE EFFECT OF SOIL MOISTURE ON EVAPOTRANSPIRATION IS DETER-
C        MINED AND ANY LOSSES TO DEEP PERCOLATION ARE EVALUATED.
C*****************************************************************
  217 IF(AVMS(I,J).GT.FTAM(I))GO TO 209
      IF((FTAM(I)-AVMS(I,J)).GT.ADPL(I))GO TO 56
      GO TO 59
   56 WARN(I,J)=1
      NEPDY(I)=NEPDY(I)+1
      IF(NEPDY(I).EQ.1)GO TO 57
      DEPSS(I,J)=ETA(I,J)-ETAM(I,J)

      DEPSM(I)=DEPSM(I)+DEPSS(I,J)
      GO TO 59
   57 DEPSM(I)=FTAM(I)-AVMS(I,J)-ADPL(I)
      GO TO 59
  209 OVER(I,J)=AVMS(I,J)-FTAM(I)
      IF(DIRI.EQ.0.0)GO TO 305
      IF(PRCP(J).EQ.0.0)GO TO 310
      OVERA=OVER(I,J)+PRCP(J)
      IF(OVERA.GT.0.0)GO TO 315
      OVERP(I)=OVERP(I)+OVERA
      GO TO 320
  315 OVERI(I)=OVERA+OVERI(I)
      OVERP(I)=OVERP(I)+PRCP(J)
      GO TO 320
  305 OVERP(I)=OVER(I,J)+OVERP(I)
      GO TO 320
  310 OVERI(I)=OVER(I,J)+OVERI(I)
  320 AVMS(I,J)=FTAM(I)
      AVMSX(I,J)=FTAM(I)
   59 AMMS(I)=AVMS(I,J)
      AMMSX(I)=AVMSX(I,J)
      CKCC(I)=CKC(I,J)
      CALL DEPLKC
      DKA(I)=DKC(I)
   60 CONTINUE
      FAVMSX(I)=FTAM(I)-AMMSX(I)
      FAVMS(I)=FTAM(I)-AMMS(I)
   50 CONTINUE
      DO 192 I=1,IFKP
      DO 193 J=NSAVE+1,NEND
      IF(DRI(I,J).EQ.1)GO TO 194
      GO TO 193
  194 SDRIR(I)=SDRIR(I)+FDIRI(I)
      NIRI(I)=NIRI(I)+1
      ADRIR(I)=FDIRI(I)
  193 CONTINUE
  192 CONTINUE
C
C       THE PROGRAM NOW EXECUTES THE PREDICTION OF THE NEXT IRRIGATION
C*****************************************************************
      DO 200 I=1,IFKP
      ETAES(I)=FAVMSX(I)
      ETAEM(I)=FAVMS(I)
      AMMSE(I)=AMMS(I)
      J=NEND+1
      DO 211 JJ=NEND+1,NEND+50
      IF(J.GT.366)J=1

      EVAPE(J)=2.4+COS(0.0172*(J)+0.2518)*5.5
      CALL CROPKC
      ETAE(I,J)=EVAPE(J)+CKC(I,J)
      ETAES(I)=ETAES(I)+ETAE(I,J)
      ETAEX=AMMSE(I)-ETAE(I,J)
```

```
      IF(((FTAM(I)-ETAEX)/FTAM(I)).LE.DDPL(I))GO TO 215
      EEE=(ETAEX/FTAM(I))*(1/(1-DDPL(I)))
      ETAEP(I,J)=ETAE(I,J)*EEE
      GO TO 216
  215 ETAEM(I,J)=ETAE(I,J)
  216 ETAEMS(I)=ETAEMS(I)+ETAEM(I,J)
      CALL DEPLKC
      RETE=ETAEMS(I)/ETAES(I)
      IF(RITE.LT.DSC(I))GO TO 280
      IF(ETAEMS(I).GT.FDIRI(I))GO TO 280
      AVMSE(I,J)=AVMSE(I)-ETAEM(I,J)
      GO TO 219
  280 ND=J
      CALL MONDAY
      IDIR(I)=IDYS
      MTIR(I)=MTTH
      GO TO 200
  219 AMMSE(I)=AVMSE(I,J)
      J=J+1
  211 CONTINUE
  200 CONTINUE
C
C       SUMMARY OF EVAPOTRANSPIRATION TOTALS AND AVERAGES AND THE
C       EXPECTED MEAN EVAPOTRANSPIRATION.
C*****************************************************************
      ETPSX=0
      DO 181 M=NSAVE-6,NSAVE
      ETPSX=ETPSX+EVAP(M)
  181 CONTINUE
      ETPAZ=0
      LL=0
      DO 182 M=NSAVE+1,NEND
      ETPAA=ETPAA+EVAP(M)
      LL=LL+1
  182 CONTINUE
      ETPAZ=ETPAA/LL
      ETPSZ=0
      DO 183 M=NSAVE+1,NEND
      ETPSZ=ETPSZ+EVAP(M)
  183 CONTINUE
      ETPTD=0
      DO 184 M=1,NEND
      ETPTD=ETPTD+EVAP(M)
  184 CONTINUE
      ETPF14=0
      DO 260 N=NEND+1,NEND+14
      ETPF14=(2.4*COS(0.0172*(N)+0.2618)+5.5)/14+ETPF14
  260 CONTINUE
      ETPF7=0
      DO 270 N=NEND+1,NEND+7
      ETPF7=(2.4*COS(0.0172*(N)+0.2618)+5.5)+ETPF7
  270 CONTINUE
  271 CALL UPDATE
      CALL CTLIST
      CALL EXPECT

      NSAVE=NEND
      WRITE(6,499)ISAVE
  499 FORMAT(' ','LAST JULIAN DAY IS ',I3)
C
C       THE PROGRAM WRITES ALL ARRAYS BACK TO DISKFILE FOR STORAGE
C       FOR THE NEXT UPDATE EXECUTION.
C*****************************************************************
  501 WRITE(1)AVMS
      WRITE(1)CKC
      WRITE(1)ETA
      WRITE(1)ETAM
      WRITE(1)ETAE
      WRITE(1)ETAEP
      WRITE(1)DVER
      WRITE(1)DEPSS
      WRITE(1)AVMSE
      WRITE(1)DRRI
      WRITE(1)WAPR
      WRITE(1)PRCP,RN,EVAP,EVAPE,SRN,SPRCP,SDRIR,SETAM,NSAVE,IFKP,FSLOP,
     $NDHRV,FSLPX,ETASS,ADMIR,OVERP,OVERI,DEPSM,NONHR,NMHHR,FDIRI,AMMS,
     $NMHRV,NNHRV,NIRI,IDIR,MTIR,FTAM,FHECT,NDCOV,NMCOV,NDCLI,NMCLI,
     $NDIRP,MDIRP,FAVMS,NMAY,ADPL,NEPDY
      WRITE(1)AVMSX
      WRITE(1)FAVMSX,DKC,DDPL
      WRITE(1)AMMSX
      WRITE(1)DKA
      LOCK 1
  500 STOP
      END
```

```
      SUBROUTINE CROPKC
C
C       THE EVALUATION OF THE CROP COEFFICIENT KNOWING THE JULIAN
C       HARVEST DAY AND THE DAYS SINCE HARVEST.
C*****************************************************************
      REAL MTTH,MTHC,MTHD,NDCOV,NMCOV,NMCLI,NDCLI,NDIRP,MDIRP,IDIR,MTIR,
     $NDNHR,NMMHR
      INTEGER YR,HRVM,HRVD,YR,DAY,YSTOR
      COMMON YR,DAY,YSTOR,ND,IDYS,MTTH,ETPSX,ETPA7,ETPS7,ETPF14,ETPF7,
     $ETPTC,MONTH,J,I,KSAVE,NEND,IFKP,AYR,JYR
      COMMON /A/ MTHA(12),MTHB(12),MTHC(12),MTHD(12),PRCP(366),
     $RN(366),ETA(15,366),ETAM(15,366),AVMS(15,366),EVAPE(36
     $6),ETAE(15,366),ETAEM(15,366),ADPL(15),FSLOP(15),NDHRV(15),FSLTX(1
     $5),ETASS(15),ADRIR(15),AVMSE(15,366),DDPL(15),DKC(15),
     $AVMSX(15,366),FAVMSX(15),AMMSX(15),DKA(15)
      COMMON /B/ FJIR(15),NMHRV(15),NNHRV(15),TAVE(366),RS(366),TMIN(36
     $6),TMAX(366),WND(366),DRRI(15,366),NDCOV(15),NMCOV(15),EVAPC3
     $66),NDCLI(366),NMCLI(366),NDIRP(15),MDIRP(15),RH(366),CKCC(15,
     $366),OVERI(15,366),FAVMS(15),SDRIR(15),NIRI(15),ETAES(15),
     $ETAEMS(15),IJIR(15),MTIR(15),FTAM(15),FHECT(15),SETAM(15)
      COMMON /C/ AMMS(15),AMMSE(15),WARN(15,366),DYAMX(15),DMAMX(15),
     $OVERF(15),OVERI(15),NEPDY(15),DEPSM(15),CKCC(15),NONHR(15),NMMHR(1
     $5),DEPSS(15,366),NNAY(366),SRN(15),SPRCP(15),AAMSE(366)
      DATA(MTHA(M),M=1,12)/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHB(N),N=1,12)/31,29,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHC(M),M=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      DATA(MTHD(N),N=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      IF(J.EQ.NMHRV(I))GO TO 119
      NDFHRV=J-NNHRV(I)
      IF(NDFHRV.LT.0)NDFHRV=NDFHRV+366
      SK=0.0036+COS(0.0172*NNHRV(I)+0.7854)+0.0097
      CK=SK+NDFHRV+0.40
      IF(CK.LE.1.0)GO TO 107
      CKCC(I,J)=1.0
  107 CKCC(I,J)=CK
      GO TO 120
  119 CKCC(I,J)=0.40
  120 RETURN
      END
```

```
      SUBROUTINE DEPLKC
C
C       THE EVALUATION OF THE IRRIGATION COEFFICIENT KNOWING THE
C       THE JULIAN DAY OF HARVEST.
C*****************************************************************
      REAL MTTH,MTHC,MTHD,NDCOV,NMCOV,NMCLI,NDCLI,NDIRP,MDIRP,IDIR,MTIR,
     $NDNHR,NMMHR
      INTEGER YR,HRVM,HRVD,YR,DAY,YSTOR
      COMMON YR,DAY,YSTOR,ND,IDYS,MTTH,ETPSX,ETPA7,ETPS7,ETPF14,ETPF7,
     $ETPTC,MONTH,J,I,KSAVE,NEND,IFKP,AYR,JYR
      COMMON /A/ MTHA(12),MTHB(12),MTHC(12),MTHD(12),PRCP(366),
     $RN(366),ETA(15,366),ETAM(15,366),AVMS(15,366),EVAPE(36
     $6),ETAE(15,366),ETAEM(15,366),ADPL(15),FSLOP(15),NDHRV(15),FSLTX(1
     $5),ETASS(15),ADRIR(15),AVMSE(15,366),DDPL(15),DKC(15),
     $AVMSX(15,366),FAVMSX(15),AMMSX(15),DKA(15)
      COMMON /B/ FJIR(15),NMHRV(15),NNHRV(15),TAVE(366),RS(366),TMIN(36
     $6),TMAX(366),WND(366),DRRI(15,366),NDCOV(15),NMCOV(15),EVAPC3
     $66),NDCLI(366),NMCLI(366),NDIRP(15),MDIRP(15),RH(366),CKCC(15,
     $366),OVERI(15,366),FAVMS(15),SDRIR(15),NIRI(15),ETAES(15),
     $ETAEMS(15),IJIR(15),MTIR(15),FTAM(15),FHECT(15),SETAM(15)
      COMMON /C/ AMMS(15),AMMSE(15),WARN(15,366),DYAMX(15),DMAMX(15),
     $OVERF(15),OVERI(15),NEPDY(15),DEPSM(15),CKCC(15),NONHR(15),NMMHR(1
     $5),DEPSS(15,366),NNAY(366),SRN(15),SPRCP(15),AAMSE(366)
      DATA(MTHA(M),M=1,12)/31,28,31,30,31,30,31,30,31,30,31/
      DATA(MTHB(N),N=1,12)/31,29,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHC(M),M=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      DATA(MTHD(N),N=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      IF(CKCC(I,J).LT.1.0)GO TO 801
      DK=0.85
      IF(NNHRV(I).GT.225)GO TO 106
      NDRYDY=30+COS(0.0224*NNHRV(I)+0.9599)+60
      GO TO 109
  106 NDRYDY=30+COS(0.0224*NNHRV(I)+3.142)+60
  109 NHH=NNHRV(I)-J
      IF(NHH.LT.0)GO TO 110
      NDTHRV=NHH
      GO TO 111
  110 NDTHRV=NHH+366
  111 IF(NDTHRV-NDRYDY.LT.0)GO TO 116
      DKC(I)=DK
      GO TO 112
  801 DKC(I)=1.0
      GO TO 112
  116 DKC(I)=0.60
  112 RETURN
      END
```

```
      SUBROUTINE MONDAY
C
C       CALCULATION OF MONTH AND DAY FROM THE JULIAN DAY.
C*****************************************************************
      REAL MTH,MTHC,MTHD,NDCOV,NMCOV,NMCLI,NOCLI,NOIRP,MOIRP,IDIR,MTIR,
     $NDNHR,NMNHR
      INTEGER YRR,HRVM,HRVD,YR,DAY,YSTOR
      COMMON YR,DAY,YSTOR,ND,IDYS,MTH,ETPSX,ETPAF,ETPSF,ETPFI4,ETPFF,
     $ETPTD,MONTH,J,I,KSAVE,NEND,IFKP,AYR,JYR
      COMMON /A/ MTHA(12),MTHB(12),MTHC(12),MTHD(12),PRCP(366),
     $RN(366),ETA(15,366),ETAM(15,366),AVMS(15,366),EVAPE(36
     $6),ETAE(15,366),ETAEM(15,366),ADPL(15),FSLDP(15),NDHRV(15),FSLTX(1
     $5),ETASS(15),ADRIR(15),AVMSE(15,366),ODPL(15),DKC(15),
     $AVMSX(15,366),FAVMSX(15),AMMSX(15),DKA(15)
      COMMON /B/ FDIRI(15),NMHRV(15),NNHRV(15),TAVE(366),RS(366),TMIN(36
     $6),TMAX(366),WND(366),DRRI(15,366),NDCOV(15),EVAPE(3
     $66),NOCLI(366),NMCLI(366),NOIRP(15),MOIRP(15),RH(366),CKC(15,
     $366),OVER(15,366),FAVMS(15),SORIR(15),NIRI(15),ETAES(15),
     $ETAEM(15),IDIR(15),MTIR(15),FTAM(15),FHECT(15),SETAM(15)
      COMMON /C/ AMMS(15),AMMSE(15),WARN(15,366),DYAMX(15),DMAMX(15),
     $OVERF(15),OVERI(15),NEPDY(15),DEPSM(15),CACC(15),NDNHR(15),NMMHR(1
     $5),DEPSS(15,366),NNAY(366),SRN(15),SPRCP(15),AAMS(366)
      DATA(MTHA(M),M=1,12)/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHB(N),N=1,12)/31,29,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHC(P),M=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      DATA(MTHD(N),N=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      IF(YSTOR.EQ.2)GO TO 169
      K=1
      IDDR=ND
      IF(IDDR.LE.31)GO TO 171
      DO 160 M=1,12
      IDDR=IDDR-MTHA(M)
      K=K+1
      IF(IDDR.LE.MTHA(M+1))GO TO 165
  160 CONTINUE
  165 IDYS=IDDR
      MTH=MTHC(K)
      GO TO 180
  169 K=1
      IDDR=ND
      IF(IDDR.LE.31)GO TO 172
      DO 170 N=1,12
      IDDR=IDDR-MTHB(N)
      K=K+1
      IF(IDDR.LE.MTHB(N+1))GO TO 175
  170 CONTINUE
  175 IDYS=IDDR
      MTH=MTHC(K)
      GO TO 180
  171 IDYS=IDDR
      MTH=MTHC(1)
      GO TO 180

  172 IDYS=IDDR
      MTH=MTHD(1)
      GO TO 180
  180 RETURN
      END
```

```
      SUBROUTINE NDAY
C
C       CALCULATION OF THE JULIAN DAY FROM YEAR, MONTH, AND DAY.
C*****************************************************************
      REAL MTH,MTHC,MTHD,NDCOV,NMCOV,NMCLI,NOCLI,NOIRP,MOIRP,IDIR,MTIR,
     $NDNHR,NMNHR
      INTEGER YRR,HRVM,HRVD,YR,DAY,YSTOR
      COMMON YR,DAY,YSTOR,ND,IDYS,MTH,ETPSX,ETPAF,ETPSF,ETPFI4,ETPFF,
     $ETPTD,MONTH,J,I,KSAVE,NEND,IFKP,AYR,JYR
      COMMON /A/ MTHA(12),MTHB(12),MTHC(12),MTHD(12),PRCP(366),
     $RN(366),ETA(15,366),ETAM(15,366),AVMS(15,366),EVAPE(36
     $6),ETAE(15,366),ETAEM(15,366),ADPL(15),FSLDP(15),NDHRV(15),FSLTX(1
     $5),ETASS(15),ADRIR(15),AVMSE(15,366),ODPL(15),DKC(15),
     $AVMSX(15,366),FAVMSX(15),AMMSX(15),DKA(15)
      COMMON /B/ FDIRI(15),NMHRV(15),NNHRV(15),TAVE(366),RS(366),TMIN(36
     $6),TMAX(366),WND(366),DRRI(15,366),NDCOV(15),NMCOV(15),EVAPE(3
     $66),NOCLI(366),NMCLI(366),NOIRP(15),MOIRP(15),RH(366),CKC(15,
     $366),OVER(15,366),FAVMS(15),SORIR(15),NIRI(15),ETAES(15),
     $ETAEM(15),IDIR(15),MTIR(15),FTAM(15),FHECT(15),SETAM(15)
      COMMON /C/ AMMS(15),AMMSE(15),WARN(15,366),DYAMX(15),DMAMX(15),
     $OVERF(15),OVERI(15),NEPDY(15),DEPSM(15),CACC(15),NDNHR(15),NMMHR(1
     $5),DEPSS(15,366),NNAY(366),SRN(15),SPRCP(15),AAMS(366)
      DATA(MTHA(M),M=1,12)/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHB(N),N=1,12)/31,29,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHC(M),M=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      DATA(MTHD(N),N=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      IF(MOD(YR,4).EQ.0)GO TO 125
      MNTH=0
      IF(MONTH.EQ.1)GO TO 137
      DO 128 M=1,MONTH-1
      MNTH=MTHA(M)+MNTH
  128 CONTINUE
      GO TO 139
  125 MNTH=0
      IF(MONTH.EQ.1)GO TO 137
      DO 130 N=1,MONTH-1
      MNTH=MTHB(N)+MNTH
  130 CONTINUE
  139 ND=MNTH+DAY
      GO TO 143
  137 ND=DAY
  143 RETURN
      END
```

```
      SUBROUTINE UPDATE
C
C      FIRST SECTION OF THE PRINTOUT. COMPRISES THE TITLE AND LIST-
C      ING OF THE CLIMATE FACTORS DURING THE UPDATE PERIOD.
C*****************************************************************
      REAL MTH,MTHC,MTHD,NDCOV,NMCOV,NMCLI,NDCLI,NDIRP,MDIRP,IDIR,MTIR,
     $NDNHR,NMNHR
      INTEGER YRR,HRVM,HRVD,YR,DAY,YSTOR
      COMMON YR,DAY,YSTOR,ND,IDYS,MTH,ETPSX,ETPA7,ETPS7,ETPF14,ETPF7,
     $ETPTD,MONTH,J,I,NSAVE,NEND,IFKP,AYR,JYR
      COMMON /A/ MTHA(12),MTHB(12),MTHC(12),MTHD(12),PRCP(366),
     $RN(366),ETA(15,366),ETAM(15,366),AVMS(15,366),EVAPE(36
     $6),ETAE(15,366),ETAEM(15,366),ADPL(15),FSLDP(15),NDHRV(15),FSLTX(1
     $5),ETASS(15),ADRIR(15),AVMSE(15,366),DDPL(15),DKC(15),
     $AVMSX(15,366),FAVMSX(15),AMMSX(15),DKA(15)
      COMMON /B/ FDIRI(15),NMHRV(15),NNHRV(15),TAVE(366),RS(366),TMIN(36
     $6),TMAX(366),WND(366),DRRI(15,366),NDCOV(15),NMCOV(15),EVAPE3
     $66),NDCLI(366),NMCLI(366),NDIRP(15),MDIRP(15),RH(366),CKC(15,
     $366),OVERI(15,366),FAVMS(15),SDRIR(15),NIRI(15),ETAES(15),
     $ETAEMS(15),IDIR(15),MTIR(15),FTAM(15),FHECT(15),SETAM(15)
      COMMON /C/ AMMS(15),AMMSE(15),WARN(15,366),DYAMX(15),DMAMX(15),
     $OVERF(15),OVERI(15),NEPOY(15),DEPSM(15),CKCC(15),NDNHR(15),NMNHR(1
     $5),DEPSS(15,366),NNAY(366),SRN(15),SPRCP(15),AAMS(366)
      DATA(MTHA(M),M=1,12)/31,28,31,30,31,30,31,30,31,30,31/
      DATA(MTHB(N),N=1,12)/31,29,31,30,31,30,31,30,31,30,31/
      DATA(MTHC(M),M=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      DATA(MTHD(N),N=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      WRITE(6,495)
405 FORMAT('1',T33,'RHODESIA SUGAR ASSOCIATION')
      WRITE(6,404)
404 FORMAT(' ',T33,26('-'),//)
      WRITE(6,403)YR
403 FORMAT(' ',T32,'YEAR',I5,/)
      WRITE(6,406)
406 FORMAT(' ',T32,'IRRIGATION SCHEDULING REPORT',/)
      WRITE(6,407)
407 FORMAT(' ',T47,'DAILY CLIMATIC DATA FOR CURRENT UPDATE',/)
      WRITE(6,408)
408 FORMAT(' ',T37,'TEMPERATURE        SOLAR      RELATIVE   WINDRUN   R
     $AIN      PAN')
      WRITE(6,410)
410 FORMAT(' ',T29,'DATE   MAX  MIN  MEAN   RADIATION   HUMIDITY    KM/
     $DAY    FALL   EVAPORATION')
      WRITE(6,412)
412 FORMAT(' ',T37,'CENTIGRADE      LNGLYS/DAY   PER CENT',14X,'MM
     $   MM',/)
      DO 415 M=NSAVE+1,NEND
      WRITE(6,420)MCLI(M),TMAX(M),TMIN(M),TAVE(M),RS(M),RH(M),
     $WND(M),RN(M),EVAP(M)
420 FORMAT(' ',T28,A3,I3,2X,2(F4.1,1X),F4.1,5X,F5.1,6X,F5.0,5X,F5.1,4X
     $,F5.1,6X,F4.1)
415 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE EFLIST
C
C      SECOND SECTION OF THE PRINTOUT. COMPRISES THE TOTALS AND
C      AVERAGES OF PAST AND EXPECTED EVAPOTRANSPIRATION (PAN
C      EVAPORATION).
C*****************************************************************
      REAL MTH,MTHC,MTHD,NDCOV,NMCOV,NMCLI,NDCLI,NDIRP,MDIRP,IDIR,MTIR,
     $NDNHR,NMNHR
      INTEGER YRR,HRVM,HRVD,YR,DAY,YSTOR
      COMMON YR,DAY,YSTOR,ND,IDYS,MTH,ETPSX,ETPA7,ETPS7,ETPF14,ETPF7,
     $ETPTD,MONTH,J,I,NSAVE,NEND,IFKP,AYR,JYR
      COMMON /A/ MTHA(12),MTHB(12),MTHC(12),MTHD(12),PRCP(366),
     $RN(366),ETA(15,366),ETAM(15,366),AVMS(15,366),EVAPE(36
     $6),ETAE(15,366),ETAEM(15,366),ADPL(15),FSLDP(15),NDHRV(15),FSLTX(1
     $5),ETASS(15),ADRIR(15),AVMSE(15,366),DDPL(15),DKC(15),
     $AVMSX(15,366),FAVMSX(15),AMMSX(15),DKA(15)
      COMMON /B/ FDIRI(15),NMHRV(15),NNHRV(15),TAVE(366),RS(366),TMIN(36
     $6),TMAX(366),WND(366),DRRI(15,366),NDCOV(15),NMCOV(15),EVAPE3
     $66),NDCLI(366),NMCLI(366),NDIRP(15),MDIRP(15),RH(366),CKC(15,
     $366),OVERI(15,366),FAVMS(15),SDRIR(15),NIRI(15),ETAES(15),
     $ETAEMS(15),IDIR(15),MTIR(15),FTAM(15),FHECT(15),SETAM(15)
      COMMON /C/ AMMS(15),AMMSE(15),WARN(15,366),DYAMX(15),DMAMX(15),
     $OVERF(15),OVERI(15),NEPOY(15),DEPSM(15),CKCC(15),NDNHR(15),NMNHR(1
     $5),DEPSS(15,366),NNAY(366),SRN(15),SPRCP(15),AAMS(366)
      DATA(MTHA(M),M=1,12)/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHB(N),N=1,12)/31,29,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHC(M),M=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      DATA(MTHD(N),N=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      WRITE(6,440)ETPSX,ETPA7
440 FORMAT(' ',//,1X,'SUM OF PAN EVAP WEEK PRECEDING = ',F5.1,' MM',T8
     $5,'AVERAGE UPDATE PERIOD PAN EVAP = ',F4.1,' MM')
      WRITE(6,442)ETPS7,ETPF14
442 FORMAT(' ','SUM OF PAN EVAP THIS UPDATE PERIOD = ',F5.1,' MM',T85,
     $'AVERAGE EXPECTED 14 DAY PAN EVAP = ',F4.1,' MM')
      WRITE(6,444)ETPF7
444 FORMAT(' ','SUM OF PAN EVAP NEXT WEEK = ',F4.1,' MM')
      WRITE(6,446)ETPTD
446 FORMAT(' ','SUM OF PAN EVAP SINCE JAN 1 IS = ',F6.1,' MM')
      RETURN
      END
```

```
      SUBROUTINE EXPECT
C
C       THIRD SECTION OF THE PRINTOUT. A LISTING OF ALL FIELD CONSTANTS
C       AND VARIABLES + SOIL MOISTURE AND IRRIGATION UPDATE AND PRE-
C       DICTION + ACCUMULATED MOISTURE LOSSES TO DEEP PERCOLATION AND
C       ACCUMULATED SOIL MOISTURE STRESS COMPONENT.
C*****************************************************************
      REAL MTH,MTHC,MTHD,NDCOV,NMCOV,NMCLI,NDCLI,NDIRP,MDIRP,IDIR,MTIR,
     $NDNHR,NMNHR
      INTEGER YRR,HRVM,HRVD,YR,DAY,YSTOR
      COMMON YR,DAY,YSTOR,ND,IDYS,MTTH,ETPSX,ETPAY,ETPS7,ETPF14,ETPF7,
     $ETPTD,MONTH,J,I,NSAVE,NEND,IFKP,AYR,JYR
      COMMON /A/ MTHA(12),MTHB(12),MTHC(12),MTHD(12),PRCP(366),
     $RN(366),ETA(15,366),ETAM(15,366),AVMS(15,366),EVAPE(36
     $6),ETAE(15,366),ETAEM(15,366),ADPL(15),FSLDP(15),NDHRV(15),FSLTX(1
     $5),ETASS(15),ADRIR(15),AVMSE(15,366),DDPL(15),DKC(15),
     $AVMSX(15,366),FAVMSX(15),AMMSX(15),DKA(15)
      COMMON /B/ FJIRI(15),NMHRV(15),NNHRV(15),TAVE(366),RS(366),TMIN(36
     $6),TMAX(366),WND(366),DRRI(15,366),NDCOV(15),NMCOV(15),EVAPC3
     $66),NDCLI(366),NMCLI(366),NDIRP(15),MDIRP(15),RH(366),CKC(15,
     $366),DVER(15,366),FAVMSE(15),SDRIR(15),NIRI(15),ETAES(15),
     $ETAEMS(15),IDIR(15),MTIR(15),FTAM(15),FHECT(15),SETAM(15)
      COMMON /C/ AMMS(15),AMMSE(15),WARN(15,366),DYAMX(15),DMAMX(15),
     $OVERP(15),OVERI(15),WEPDY(15),DEPSM(15),CKCC(15),NDNHR(15),NMMHR(1
     $5),DEPSS(15,366),NMAY(366),SRN(15),SPRCP(15),AAMS(366)
      DATA(MTHA(M),M=1,12)/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHB(M),M=1,12)/31,29,31,30,31,30,31,31,30,31,30,31/
      DATA(MTHC(M),M=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      DATA(MTHD(M),M=1,12)/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AU
     $G','SEP','OCT','NOV','DEC'/
      WRITE(6,459)
459 FORMAT(' ',//,1X,T32,'ND',18X,'FULL    NEXT      "IRRIGATION UPDATE
     $AND PREDICTION"          ACCUM  ACCUM  ACCUM')
      WRITE(6,460)
460 FORMAT(' ',T13,'SOIL ROOT          STRESS IRRIG  CROP  CANOPY HARV
     $ST DEPLTN LAST  AMOUNT  #IRRIG AMOUNT  NEXT     PRECIP IRRIG  MOIS
     $TURE')
      WRITE(6,462)
462 FORMAT(' ',T2,'FLD  HECT  TYPE ZONE   TAM    MAD   COEFF  COEFF  D
     $ATE   DATE  TODATE  IRRIG APPLIED TODATE TODATE  IRRIG   LOSSES LO
     $SSES DEFICIT')
      WRITE(6,465)
465 FORMAT(' ',T3,'#',15X,'CM     MM      MM',33X,'MM              MM
     $      MM              MM      MM      MM')
      WRITE(6,466)
466 FORMAT(' ',128('-'),/)
      DO 467 IF=1,IFKP
      WRITE(6,468)IF,FHECT(IF),FSLTX(IF),FSLDP(IF),FTAM(IF),ADPL(IF),DKA
     $(IF),CKCC(IF),NMCOV(IF),NDCOV(IF),NMMHR(IF),NDNHR(IF),FAVMS(IF),MD
     $IRP(IF),NDIRP(IF),ADRIR(IF),NIRI(IF),SDRIR(IF),MTIR(IF),IDIR(IF),D
     $VERP(IF),OVERI(IF),DEPSM(IF)
468 FORMAT(1X,I2,2X,F5.1,2X,A3,1X,3(F5.1,2X),2(F5.2,2X),2(A3,I3,1X),F5
     $.1,2X,A3,T3,1X,F5.1,I6,3X,F6.1,3X,A3,I3,3(F7.1))
467 CONTINUE
      WRITE(6,472)
472 FORMAT(' ',///,T10,'THE FOLLOWING FIELDS EXPERIENCED CONTROLLED')
      WRITE(6,473)
473 FORMAT(' ',T10,'   STRESS DURING THE CURRENT UPDATE PERIOD :',/)
      KADPL=0
      DO 475 I=1,IFKP
      DO 476 J=NSAVE+1,NEND
      IF(WARN(I,J).EQ.1)GO TO 477
      GO TO 476
477 KADPL=KADPL+1
      ND=J
      CALL MONDAY
      DYAMX(I)=IDYS
      DMAMX(I)=MTTH
      WRITE(6,481)I,DMAMX(I),DYAMX(I)
481 FORMAT(' ',T55,'FIELD NUMBER ',I2,' FROM ',A3,I3)
      GO TO 475
476 CONTINUE
475 CONTINUE
      IF(KADPL.EQ.0)WRITE(6,483)
483 FORMAT(' ',T55,'ALL FIELDS ADEQUATE')
      RETURN
      END
```

A TYPICAL INPUT DECK WITH THE INITIALISING OF NEW FIELD VALUES
AND THE UPDATE CLIMATE DATA AND THE IRRIGATION THAT TOOK PLACE
DURING THE UPDATE PERIOD.
THE INPUT DECK IS:

```
C       SYSTEM CONTROL CARDS INSERTED HERE.
? DATA
0
1111
555                                THESE ARE THE OPTION FILLER
2222                               CARDS AS DEFINED IN THE
333                                PROGRAM AND THE TEXT.
444
 06  1974 05   01     30.4 91.0110.0 0.50 45.0SCL    0.11
 07  1974 05   01     26.6 51.0 69.0 0.50 45.0SCL    0.25
 08  1974 05   08     14.7 36.0 53.0 0.65 45.0LS     0.15
888                                FILLER CARD TO CLOSE FIELD INPUT
19745C1 275  142  000C 545  78   12   193  167  153  107  23   031
19745C2 276  117  000C 538  73   11   191  159  140  107  10   035
19745C3 263  125  000C 439  77   14   198  172  160  092  25   028
19745C4 293  131  000C 524  76   14   206  177  162  104  12   038
19745C5 297  137  000C 517  76   13   212  183  169  100  18   029
19745C6 3C6  148  C004 507  78   14   220  194  182  089  22   036
19745C7 292  171  001F 442  78   31   215  187  173  058  5C   033
19745C8 223  168  000C 238  84   24   190  172  161  012  75   018
19745C9 174  134  CC3E 153  90   14   156  145  139  000  80   002
19745C10 213 136  000C 211  88   13   169  156  148  012  75   011
19745C11 217 144  0030 251  84   08   172  155  144  014  71   014
19745C12 27C 090  CC0C 511       09                   104  06   033
9999                               FILLER CARD TO CLOSE CLIMATE INPUT
 01  05   C3
 04  05   C9
 05  05   C2
 06  05   C4
 06  05   11
 07  05   C9
 08  05   12
 11  05   10
 14  05   C3
777                                FILLER CARD TO CLOSE IRRIGATION INPUT
? END
```

THE USE OF THE VARIOUS OPTION CARDS IS EXPLAINED IN THE BODY
OF THE TEXT, AND THEIR USE MUST BE CAREFULLY NOTED. WHEN USING
ANY OF THE OPTIONS, NO CLIMATE OR IRRIGATION DATA MUST BE
INPUTED AT THE SAME TIME.

Appendix C

Irrigation Scheduling Printouts

Irrigation Schedule Printout for the period indicated.

RHODESIA SUGAR ASSOCIATION

YEAR 1973

IRRIGATION SCHEDULING REPORT

DAILY CLIMATIC DATA FOR CURRENT UPDATE

DATE	TEMPERATURE MAX CENTIGRADE	TEMPERATURE MIN CENTIGRADE	TEMPERATURE MEAN CENTIGRADE	SOLAR RADIATION LANGLYS/DAY	RELATIVE HUMIDITY PER CENT	WINDRUN KM/DAY	RAIN FALL MM	PAN EVAPORATION MM
JUN 3	28.0	10.2	19.1	361.0	62.	65.6	0.0	3.6
JUN 4	27.4	10.3	18.9	405.0	59.	69.5	0.0	3.9
JUN 5	27.1	8.7	17.9	422.0	52.	69.5	0.0	4.1
JUN 6	27.4	8.5	18.0	374.0	57.	81.1	0.0	3.1
JUN 7	25.8	9.4	17.6	313.0	63.	81.1	0.0	3.2
JUN 8	25.2	8.9	17.1	415.0	58.	85.0	0.0	4.1
JUN 9	23.8	8.3	16.1	391.0	59.	92.7	0.0	3.6
JUN 10	21.0	13.1	17.1	265.0	77.	119.7	2.9	1.6
JUN 11	23.0	13.9	18.5	303.0	82.	150.6	4.9	2.3
JUN 12	20.9	12.1	16.5	245.0	81.	85.6	0.3	2.2

SUM OF PAN EVAP WEEK PRECEDING = 24.8 MM
SUM OF PAN EVAP THIS UPDATE PERIOD = 31.7 MM
SUM OF PAN EVAP NEXT WEEK = 21.7 MM
SUM OF PAN EVAP SINCE JAN 1 IS = 961.4 MM

AVERAGE UPDATE PERIOD PAN EVAP = 3.2 MM
AVERAGE EXPECTED 14 DAY PAN EVAP = 3.1 MM

FLD #	HECT	SOIL TYPE	ROOT ZONE CM	TAM MM	MAC MM	IRRIG COEFF	CROP COEFF	FULL CANOPY DATE	NEXT HARVST DATE	*IRRIGATION UPDATE AND PREDICTION* DEPLTN TODATE MM	LAST IRRIG	AMOUNT APPLIED MM	#IRRIG TODATE	AMOUNT TODATE MM	NEXT IRRIG	ACCUM PRECIP LOSSES MM	ACCUM IRRIG LOSSES MM	ACCUM MOISTURE DEFICIT MM
1	30.4	SCL	91.0	110.0	55.0	0.85	1.00	FEB 21	JAN 1	31.6	JUN 1	45.0	16	720.0	JUN 17	24.6	35.9	26.3
2	26.6	SCL	51.0	69.0	34.5	0.85	1.00	FEB 21	JAN 1	17.4	JUN 4	45.0	16	720.0	JUN 22	44.5	89.7	50.6
3	14.7	LS	36.0	53.0	34.5	0.85	1.00	MAR 6	JAN 12	1.9	JUN 11	45.0	14	630.0	JUN 29	53.3	70.1	115.4
4	38.4	CL	91.0	218.0	87.2	0.85	1.00	MAR 16	JAN 20	43.6	MAY 28	60.0	10	600.0	JUN 18	3.5	24.2	32.9
5	43.2	CL	51.0	82.0	32.8	0.85	1.00	MAR 25	JAN 27	26.6	JUN 1	60.0	11	660.0	JUN 25	40.3	196.7	39.5
6	30.4	SCL	91.0	110.0	55.0	1.00	0.66	AUG 7	MAY 1	14.8	JUN 2	45.0	3	135.0	JUN 26	0.0	0.0	25.2
7	26.6	SCL	51.0	69.0	34.5	1.00	0.66	AUG 7	MAY 1	7.3	JUN 4	45.0	3	135.0	JUN 25	0.0	17.6	26.9
8	14.7	LS	36.0	53.0	34.5	1.00	0.59	AUG 20	MAY 12	7.7	JUN 3	45.0	2	90.0	JUN 26	0.0	9.4	48.6
9	38.4	CL	91.0	218.0	87.2	1.00	0.54	AUG 28	MAY 20	29.0	MAY 28	60.0	2	120.0	JUN 29	0.0	0.0	27.5
10	43.2	CL	51.0	82.0	32.8	1.00	0.50	SEP 3	MAY 27	10.5	MAY 30	60.0	1	60.0	JUN 26	0.0	4.8	4.6

THE FOLLOWING FIELDS EXCEEDED THE ALLOWABLE
DEPLETION DURING THE CURRENT UPDATE PERIOD :

FIELD NUMBER 2 ON JUN 3
FIELD NUMBER 3 ON JUN 5

LAST JULIAN DAY IS 163

Irrigation Schedule Printout for the period indicated.

RHODESIA SUGAR ASSOCIATION

YEAR 1973

IRRIGATION SCHEDULING REPORT

DAILY CLIMATIC DATA FOR CURRENT UPDATE

DATE	TEMPERATURE MAX CENTIGRADE	TEMPERATURE MIN CENTIGRADE	TEMPERATURE MEAN CENTIGRADE	SOLAR RADIATION LANGLEYS/DAY	RELATIVE HUMIDITY PER CENT	WINDRUN KM/DAY	RAIN FALL MM	PAN EVAPORATION MM
JUN 13	21.3	12.9	17.1	193.0	84.	61.8	0.0	1.4
JUN 14	25.1	8.0	16.6	371.0	71.	27.0	0.0	2.3
JUN 15	26.6	13.9	20.3	343.0	57.	65.6	0.0	2.5
JUN 16	25.6	14.1	19.9	303.0	68.	50.2	0.0	2.6
JUN 17	26.5	9.9	18.2	340.0	59.	42.5	0.0	2.8
JUN 18	27.2	9.0	18.1	425.0	46.	77.2	0.0	4.2
JUN 19	27.4	8.3	17.9	408.0	48.	46.3	0.0	3.5
JUN 20	29.1	9.0	19.1	419.0	41.	73.4	0.0	3.8
JUN 21	23.9	13.4	18.7	275.0	65.	100.4	0.0	3.2
JUN 22	23.0	12.1	17.6	241.0	62.	77.2	0.0	2.6

SUM OF PAN EVAP WEEK PRECEDING = 20.1 MM
SUM OF PAN EVAP THIS UPDATE PERIOD = 28.9 MM
SUM OF PAN EVAP NEXT WEEK = 21.9 MM
SUM OF PAN EVAP SINCE JAN 1 IS = 990.3 MM

AVERAGE UPDATE PERIOD PAN EVAP = 2.5 MM
AVERAGE EXPECTED 14 DAY PAN EVAP = 3.2 MM

FLD #	HECT	SOIL TYPE	ROOT ZONE CM	TAW MM	MAD MM	IRRIG COEFF	CROP COEFF	FULL CANOPY DATE	NEXT HARVST DATE	"IRRIGATION UPDATE AND PREDICTION" DEPLTN TODATE MM	LAST IRRIG	AMOUNT APPLIED MM	#IRRIG TODATE	AMOUNT TODATE MM	NEXT IRRIG	ACCUM PRECIP LOSSES MM	ACCUM IRRIG LOSSES MM	ACCUM MOISTURE DEFICIT MM
1	30.4	SCL	91.0	110.0	55.0	0.85	1.00	FEB 21	JAN 1	17.3	JUN 17	45.0	17	765.0	JUL 1	24.6	37.7	28.3
2	26.6	SCL	51.0	69.0	34.5	0.85	1.00	FEB 21	JAN 1	0.0	JUN 22	45.0	17	765.0	JUL 8	44.5	90.8	52.2
3	14.7	LS	36.0	53.0	34.5	0.85	1.00	MAR 6	JAN 12	30.6	JUN 11	45.0	14	630.0	JUN 29	53.3	70.1	115.4
4	38.4	CL	91.0	218.0	87.2	0.85	1.00	MAR 16	JAN 20	72.5	MAY 28	60.0	10	600.0	JUN 23	3.5	24.2	32.5
5	43.2	CL	51.0	82.0	32.8	0.85	1.00	MAR 25	JAN 27	50.2	JUN 1	60.0	11	660.0	JUN 26	40.3	196.7	44.6
6	30.4	SCL	91.0	110.0	55.0	1.00	0.72	AUG 7	MAY 1	35.0	JUN 2	45.0	3	135.0	JUN 27	0.0	0.0	25.2
7	26.6	SCL	51.0	69.0	34.5	1.00	0.72	AUG 7	MAY 1	27.5	JUN 4	45.0	3	135.0	JUN 26	0.0	17.6	26.9
8	14.7	LS	36.0	53.0	34.5	1.00	0.65	AUG 20	MAY 12	25.8	JUN 3	45.0	2	90.0	JUN 27	0.0	9.4	48.6
9	38.4	CL	91.0	218.0	87.2	1.00	0.60	AUG 28	MAY 20	45.6	MAY 28	60.0	2	120.0	JUN 30	0.0	0.0	27.5
10	43.2	CL	51.0	82.0	32.8	1.00	0.56	SEP 3	MAY 27	26.0	MAY 30	60.0	1	60.0	JUN 26	0.0	4.8	4.6

THE FOLLOWING FIELDS EXCEEDED THE ALLOWABLE
DEPLETION DURING THE CURRENT UPDATE PERIOD :

FIELD NUMBER 2 ON JUN 19
FIELD NUMBER 5 ON JUN 16

LAST JULIAN DAY IS 173

Irrigation Schedule Printout for the period indicated.

PHOENIX SUGAR ASSOCIATION

YEAR 1973

IRRIGATION SCHEDULING REPORT

DAILY CLIMATIC DATA FOR CURRENT UPDATE

DATE	TEMPERATURE MAX CENTIGRADE	MIN	MEAN	SOLAR RADIATION LANGLYS/DAY	RELATIVE HUMIDITY PER CENT	WINDRUN KM/DAY	RAIN FALL MM	PAN EVAPORATION MM
JUN 23	23.0	10.4	16.7	234.0	69.	77.2	0.0	1.6
JUN 24	22.0	9.6	15.8	234.0	71.	77.2	0.0	2.2
JUN 25	23.0	8.5	15.8	381.0	57.	85.0	0.0	3.7
JUN 26	22.5	15.5	19.0	248.0	64.	127.4	0.0	3.0
JUN 27	21.4	14.9	18.2	156.0	76.	77.2	0.4	1.3
JUN 28	21.2	15.0	18.1	197.0	74.	50.2	0.0	2.0
JUN 29	27.4	12.5	20.0	374.0	55.	69.5	0.0	3.5
JUN 30	28.4	6.0	18.2	398.0	46.	46.3	0.0	3.9
JUL 1	28.0	8.4	18.2	415.0	44.	88.6	0.0	4.6
JUL 2	25.7	9.3	17.5	361.0	60.	65.6	0.0	3.4
JUL 3	27.5	8.8	18.2	367.0	57.	54.1	0.0	3.1

SUM OF PAN EVAP WEEK PRECEDING = 22.7 MM
SUM OF PAN EVAP THIS UPDATE PERIOD = 32.5 MM
SUM OF PAN EVAP NEXT WEEK = 22.7 MM
SUM OF PAN EVAP SINCE JAN 1 IS = 1022.8 MM

AVERAGE UPDATE PERIOD PAN EVAP = 3.0 MM
AVERAGE EXPECTED 14 DAY PAN EVAP = 3.3 MM

FLD #	HEIGT	SOIL TYPE	ROOT ZONE CM	TAM MM	MAD MM	IRRIG COEFF	CROP COEFF	FULL CANOPY DATE	NEXT HARVST DATE	"IRRIGATION UPDATE AND PREDICTION" DEPLTN TODATE MM	LAST IRRIG	AMOUNT APPLIED MM	#IRRIG TODATE	AMOUNT TODATE MM	NEXT IRRIG	ACCUM PRECIP LOSSES MM	ACCUM IRRIG LOSSES MM	ACCUM MOISTURE DEFICIT MM
1	30.4	SCL	91.0	110.0	55.0	0.85	1.00	FEB 21	JAN 1	6.5	JUL 1	45.0	18	810.0	JUL 15	24.6	39.8	26.3
2	26.6	SCL	51.0	69.0	34.5	0.85	1.00	FEB 21	JAN 1	32.1	JUL 22	45.0	17	765.0	JUL 8	44.5	90.8	52.2
3	14.7	LS	36.0	53.0	34.5	0.85	1.00	MAR 6	JAN 12	15.0	JUL 25	45.0	15	675.0	JUL 15	53.3	72.3	118.5
4	38.4	CL	91.0	218.0	87.2	0.85	1.00	MAR 16	JAN 20	44.8	JUL 23	60.0	11	660.0	JUL 6	3.5	24.2	32.9
5	43.2	CL	51.0	82.0	32.8	0.85	1.00	MAR 25	JAN 27	21.4	JUL 26	60.0	12	720.0	JUL 17	40.3	200.7	48.2
6	30.4	SCL	91.0	110.0	55.0	1.00	0.79	AUG 7	MAY 1	16.0	JUL 27	45.0	4	180.0	JUL 14	0.4	1.1	25.2
7	26.6	SCL	51.0	69.0	34.5	1.00	0.79	AUG 7	MAY 1	16.5	JUL 26	45.0	4	180.0	JUL 10	0.0	27.2	26.5
8	14.7	LS	36.0	53.0	34.5	1.00	0.72	AUG 20	MAY 12	14.4	JUL 27	45.0	3	135.0	JUL 12	0.4	20.6	48.8
9	38.4	CL	91.0	218.0	87.2	1.00	0.67	AUG 28	MAY 20	7.3	JUL 30	60.0	3	180.0	JUL 25	0.0	1.3	27.5
10	43.2	CL	51.0	82.0	32.8	1.00	0.63	SEP 3	MAY 27	12.9	JUL 28	60.0	2	120.0	JUL 13	0.0	32.6	4.8

THE FOLLOWING FIELDS EXCEEDED THE ALLOWABLE
DEPLETION DURING THE CURRENT UPDATE PERIOD :

FIELD NUMBER 3 ON JUN 24
FIELD NUMBER 5 ON JUN 23

LAST JULIAN DAY IS 184

Irrigation Schedule Printout for the period indicated.

RHODESIA SUGAR ASSOCIATION

YEAR 1974

IRRIGATION SCHEDULING REPORT

DAILY CLIMATIC DATA FOR CURRENT UPDATE

DATE	TEMPERATURE MAX CENTIGRADE	TEMPERATURE MIN CENTIGRADE	TEMPERATURE MEAN CENTIGRADE	SOLAR RADIATION LANGLYS/DAY	RELATIVE HUMIDITY PER CENT	WINDRUN MM/DAY	RAIN FALL MM	PAN EVAPORATION MM
JAN 27	32.3	19.4	25.9	644.0	71.	85.0	0.0	5.5
JAN 28	35.1	19.0	27.1	753.0	62.	92.7	0.0	7.4
JAN 29	35.5	18.9	27.2	732.0	61.	127.4	0.4	8.2
JAN 30	29.1	21.3	25.2	340.0	87.	96.5	8.6	2.7
JAN 31	28.7	19.9	24.3	473.0	85.	104.3	2.4	4.0

SUM OF PAN EVAP WEEK PRECEDING = 39.1 MM
SUM OF PAN EVAP THIS UPDATE PERIOD = 27.8 MM
SUM OF PAN EVAP NEXT WEEK = 49.4 MM
SUM OF PAN EVAP SINCE JAN 1 IS = 191.3 MM

AVERAGE UPDATE PERIOD PAN EVAP = 5.6 MM
AVERAGE EXPECTED 14 DAY PAN EVAP = 6.9 MM

FLD #	HECT	SOIL TYPE	ROOT ZONE CM	TAM MM	NO STRESS MAC MM	IRRIG COEFF	CROP COEFF	FULL CANOPY DATE	NEXT MAX ST DATE	"IRRIGATION UPDATE AND PREDICTION" DEPTH TO DATE MM	LAST IRRIG	APPLNT APPLIED MM	NO IRRIG TO DATE	AMOUNT TO DATE MM	NEXT IRRIG	ACCUM PRECIP LOSSES MM	ACCUM IRRIG LOSSES MM	ACCUM MOIS TURE DEFICIT MM
1	36.4	SCL	91.0	110.0	55.0	1.00	0.77	FEB 21	JAN 1	24.5	JAN 15	45.0	3	135.0	FEB 4	0.0	0.0	56.4
2	26.6	SCL	51.0	69.0	34.5	1.00	0.77	FEB 21	JAN 1	13.0	JAN 25	45.0	4	180.0	FEB 4	2.9	68.6	23.2
3	14.7	LS	36.0	53.0	34.5	1.00	0.62	MAR 6	JAN 12	18.4	JAN 16	45.0	1	45.0	FEB 4	0.7	0.0	19.7
4	38.4	CL	91.0	218.0	87.2	1.00	0.52	MAR 16	JAN 20	18.2	JAN 17	60.0	0	0.0	FEB 11	0.0	0.0	0.0
5	43.8	CL	51.0	82.0	32.8	1.00	0.44	MAR 25	JAN 27	0.0	JAN 30	60.0	1	60.0	FEB 10	9.2	4.3	22.4
6	36.4	SCL	91.0	110.0	55.0	0.85	1.00	AUG 7	MAY 1	24.3	JAN 24	45.0	25	1125.0	FEB 3	159.3	37.6	25.4
7	26.6	SCL	51.0	69.0	34.5	0.85	1.00	AUG 7	MAY 1	24.3	JAN 24	45.0	25	1125.0	FEB 4	238.3	149.0	100.8
8	14.7	LS	36.0	53.0	34.5	0.85	1.00	AUG 20	MAY 12	1.6	JAN 29	45.0	22	990.0	FEB 7	241.3	103.3	154.6
9	38.4	CL	91.0	218.0	87.2	0.85	1.00	AUG 26	MAY 20	1.6	JAN 29	60.0	18	1080.0	FEB 9	178.8	16.3	27.5
10	43.2	CL	51.0	82.0	32.8	0.85	1.00	SEP 3	MAY 27	43.2	JAN 17	60.0	17	1020.0	FEB 1	182.8	231.1	96.5
11	36.4	SCL	91.0	110.0	55.0	0.85	1.00	OCT 25	SEP 1	24.3	JAN 24	45.0	15	675.0	FEB 3	199.8	53.2	26.1
12	26.6	SCL	51.0	69.0	34.5	0.85	1.00	OCT 25	SEP 1	37.7	JAN 19	45.0	13	585.0	FEB 1	223.3	45.1	63.5
13	14.7	LS	36.0	53.0	34.5	0.85	1.00	NOV 6	SEP 12	1.6	JAN 29	45.0	13	585.0	FEB 7	216.1	103.9	56.6
14	38.4	CL	91.0	218.0	87.2	0.85	1.00	NOV 12	SEP 20	1.6	JAN 29	60.0	9	540.0	FEB 9	154.0	17.9	28.3
15	43.2	CL	51.0	82.0	32.8	0.85	1.00	NOV 17	SEP 27	43.2	JAN 17	60.0	8	480.0	FEB 1	178.7	146.7	55.3

THE FOLLOWING FIELDS EXPERIENCED CONTROLLED
STRESS DURING THE CURRENT UPDATE PERIOD :

FIELD NUMBER 5 FROM JAN 27
FIELD NUMBER 8 FROM JAN 27
FIELD NUMBER 10 FROM JAN 27
FIELD NUMBER 12 FROM JAN 28
FIELD NUMBER 13 FROM JAN 28
FIELD NUMBER 15 FROM JAN 27

LAST JULIAN DAY IS 31

Irrigation Schedule Printout for the period indicated.

RHODESIA SUGAR ASSOCIATION

YEAR 1974

IRRIGATION SCHEDULING REPORT

DAILY CLIMATIC DATA FOR CURRENT UPDATE

DATE	TEMPERATURE MAX CENTIGRADE	TEMPERATURE MIN CENTIGRADE	TEMPERATURE MEAN CENTIGRADE	SOLAR RADIATION LANGLYS/DAY	RELATIVE HUMIDITY PER CENT	WINDRUN KM/DAY	RAIN FALL MM	PAN EVAPORATION MM
FEB 1	30.6	19.3	25.0	545.0	76.	77.2	0.0	6.7
FEB 2	32.0	18.8	25.4	712.0	66.	104.3	0.0	6.7
FEB 3	30.4	19.6	25.0	504.0	77.	73.4	1.1	4.2
FEB 4	32.7	21.2	27.0	620.0	71.	81.1	0.0	5.8
FEB 5	32.6	20.0	26.3	541.0	73.	69.5	0.0	4.5
FEB 6	34.0	18.7	26.4	657.0	69.	73.4	0.0	6.5

SUM OF PAN EVAP WEEK PRECEDING = 36.2 MM
SUM OF PAN EVAP THIS UPDATE PERIOD = 34.4 MM
SUM OF PAN EVAP NEXT WEEK = 48.0 MM
SUM OF PAN EVAP SINCE JAN 1 IS = 225.7 MM

AVERAGE UPDATE PERIOD PAN EVAP = 5.7 MM
AVERAGE EXPECTED 14 DAY PAN EVAP = 6.7 MM

FLD #	HECT	SOIL TYPE	ROOT ZONE CM	TAM MM	NO STRESS MAD MM	IRRIG COEFF	CROP COEFF	FULL CANOPY DATE	NEXT HARV DATE	*IRRIGATION UPDATE AND PREDICTION* DEPLTN TODATE MM	LAST IRRIG	APPLIED MM	#IRRIG TODATE	AMOUNT TODATE MM	NEXT IRRIG	ACCUM PRECIP LOSSES MM	ACCUM IRRIG LOSSES MM	ACCUM MOIS TURE DEFICIT MM
1	30.4	SCL	91.0	110.0	55.0	1.00	0.84	FEB 21	JAN 1	9.2	FEB 4	45.0	4	180.0	FEB 12	0.0	2.9	56.4
2	26.6	SCL	51.0	69.0	34.5	1.00	0.84	FEB 21	JAN 1	9.2	FEB 4	45.0	5	225.0	FEB 11	2.9	83.1	23.2
3	14.7	LS	36.0	53.0	34.5	1.00	0.69	MAR 6	JAN 12	7.6	FEB 4	45.0	2	90.0	FEB 12	0.7	12.5	19.7
4	38.4	CL	91.0	218.0	87.2	1.00	0.59	MAR 16	JAN 20	36.4	JAN 17	60.0	0	0.0	FEB 12	0.0	0.0	0.0
5	43.2	CL	51.0	82.0	32.8	1.00	0.51	MAR 25	JAN 27	15.4	JAN 30	60.0	1	60.0	FEB 11	9.2	4.3	22.4
6	30.4	SCL	91.0	110.0	55.0	0.85	1.00	AUG 7	MAY 1	16.8	FEB 3	45.0	26	1170.0	FEB 11	200.4	40.7	25.4
7	26.6	SCL	51.0	69.0	34.5	0.85	1.00	AUG 7	MAY 1	11.0	FEB 4	45.0	26	1170.0	FEB 12	238.3	150.6	162.3
8	14.7	LS	36.0	53.0	34.5	0.85	1.00	AUG 20	MAY 12	34.7	JAN 29	45.0	22	990.0	FEB 9	241.3	101.3	154.7
9	38.4	CL	91.0	218.0	87.2	0.85	1.00	AUG 28	MAY 20	34.9	JAN 29	60.0	18	1080.0	FEB 10	178.8	16.3	27.5
10	43.2	CL	51.0	82.0	32.8	0.85	1.00	SEP 3	MAY 27	26.6	FEB 1	60.0	18	1080.0	FEB 12	162.8	243.5	56.5
11	38.4	SCL	91.0	110.0	55.0	0.85	1.00	OCT 29	SEP 1	16.8	FEB 3	45.0	16	720.0	FEB 11	200.9	56.4	26.1
12	26.6	SCL	51.0	69.0	34.5	0.85	1.00	OCT 29	SEP 1	26.6	FEB 1	45.0	14	630.0	FEB 10	223.3	47.6	63.5
13	14.7	LS	36.0	53.0	34.5	0.85	1.00	NOV 6	SEP 12	34.7	JAN 29	45.0	13	585.0	FEB 9	216.1	103.9	56.8
14	38.4	CL	91.0	218.0	87.2	0.85	1.00	NOV 12	SEP 20	34.9	JAN 29	60.0	9	540.0	FEB 10	154.0	17.9	28.3
15	43.2	CL	51.0	82.0	32.8	0.85	1.00	NOV 17	SEP 27	26.6	FEB 1	60.0	9	540.0	FEB 12	178.7	151.1	55.1

THE FOLLOWING FIELDS EXPERIENCED CONTROLLED
STRESS DURING THE CURRENT UPDATE PERIOD :

FIELD NUMBER 7 FROM FEB 2
FIELD NUMBER 8 FROM FEB 6
FIELD NUMBER 13 FROM FEB 6

LAST JULIAN DAY IS 37

Irrigation Schedule Printout for the period indicated.

RHODESIA SUGAR ASSOCIATION

YEAR 1974

IRRIGATION SCHEDULING REPORT

DAILY CLIMATIC DATA FOR CURRENT UPDATE

DATE	TEMPERATURE MAX CENTIGRADE	TEMPERATURE MIN CENTIGRADE	TEMPERATURE MEAN CENTIGRADE	SOLAR RADIATION LNGLYS/DAY	RELATIVE HUMIDITY PER CENT	WINDRUN KM/DAY	RAIN FALL MM	PAN EVAPORATION MM
FEB 7	35.7	19.5	27.6	623.0	73.	73.4	1.0	5.9
FEB 8	32.7	20.4	26.6	575.0	73.	123.6	27.1	6.4
FEB 9	29.2	21.3	25.3	419.0	92.	196.9	10.0	3.1

SUM OF PAN EVAP WEEK PRECEDING = 38.4 MM
SUM OF PAN EVAP THIS UPDATE PERIOD = 15.4 MM
SUM OF PAN EVAP NEXT WEEK = 47.3 MM
SUM OF PAN EVAP SINCE JAN 1 IS = 241.1 MM

AVERAGE UPDATE PERIOD PAN EVAP = 5.1 MM
AVERAGE EXPECTED 14 DAY PAN EVAP = 6.6 MM

FLD #	HECT	SOIL TYPE	ROOT ZONE CM	TAM MM	NO STRESS MAD MM	IRRIG COEFF	CROP COEFF	FULL CANOPY DATE	NEXT HARV DATE	ST	"IRRIGATION UPDATE AND PREDICTION" DEPLTN TODATE MM	LAST IRRIG	APCUNT APPLIED MM	#IRRIG TODATE	AMOUNT TODATE MM	NEXT IRRIG	ACCUM PRECIP LOSSES MM	ACCUM IRRIG LOSSES MM	ACCUM MOIS TURE DEFICIT MM
1	36.4	SCL	91.0	110.0	55.0	1.00	0.88	FEB 21	JAN 1		0.0	FEB 4	45.0	4	180.0	FEB 17	11.2	2.9	56.4
2	26.6	SCL	51.0	69.0	34.5	1.00	0.88	FEB 21	JAN 1		0.0	FEB 4	45.0	5	225.0	FEB 15	14.1	83.1	23.2
3	14.7	LS	36.0	53.0	34.5	1.00	0.73	MAR 6	JAN 12		0.0	FEB 4	45.0	2	90.0	FEB 16	15.8	12.5	19.7
4	38.4	CL	91.0	218.0	87.2	1.00	0.62	MAR 16	JAN 20		12.2	JAN 17	60.0	0	0.0	FEB 20	0.0	0.0	0.0
5	43.2	CL	51.0	82.0	32.8	1.00	0.54	MAR 25	JAN 27		0.0	JAN 30	60.0	1	60.0	FEB 18	19.3	4.3	22.4
6	36.4	SCL	91.0	110.0	55.0	0.85	1.00	AUG 7	MAY 1		0.0	FEB 3	45.0	26	1170.0	FEB 16	201.8	40.7	25.4
7	26.6	SCL	51.0	69.0	34.5	0.85	1.00	AUG 7	MAY 1		0.0	FEB 4	45.0	26	1170.0	FEB 17	245.6	150.6	102.3
8	14.7	LS	36.0	53.0	34.5	0.85	1.00	AUG 20	MAY 12		0.0	FEB 9	45.0	22	1035.0	FEB 17	251.3	127.1	156.7
9	38.4	CL	91.0	218.0	87.2	0.85	1.00	AUG 28	MAY 20		16.6	JAN 29	60.0	18	1080.0	FEB 16	178.8	16.3	27.5
10	43.2	CL	51.0	82.0	32.8	0.85	1.00	SEP 3	MAY 27		7.7	FEB 1	60.0	18	1080.0	FEB 18	182.8	243.5	96.5
11	36.4	SCL	91.0	110.0	55.0	0.85	1.00	OCT 29	SEP 1		0.0	FEB 3	45.0	16	720.0	FEB 16	202.4	56.4	26.1
12	26.6	SCL	51.0	69.0	34.5	0.85	1.00	OCT 29	SEP 1		7.7	FEB 1	45.0	14	630.0	FEB 16	223.3	47.6	83.5
13	14.7	LS	36.0	53.0	34.5	0.85	1.00	NOV 6	SEP 12		0.0	FEB 9	45.0	14	630.0	FEB 17	226.1	127.7	58.6
14	38.4	CL	91.0	218.0	87.2	0.85	1.00	NOV 12	SEP 20		16.6	JAN 29	60.0	9	540.0	FEB 16	154.0	17.9	28.3
15	43.2	CL	51.0	82.0	32.8	0.85	1.00	NOV 17	SEP 27		7.7	FEB 1	60.0	9	540.0	FEB 18	178.7	153.1	55.3

THE FOLLOWING FIELDS EXPERIENCED CONTROLLED
STRESS DURING THE CURRENT UPDATE PERIOD :

FIELD NUMBER 8 FROM FEB 7
FIELD NUMBER 13 FROM FEB 7

LAST JULIAN DAY IS 40

Irrigation Schedule Printout for the period indicated.

RHODESIA SUGAR ASSOCIATION

YEAR 1974

IRRIGATION SCHEDULING REPORT

DAILY CLIMATIC DATA FOR CURRENT UPDATE

DATE	TEMPERATURE MAX CENTIGRADE	TEMPERATURE MIN CENTIGRADE	TEMPERATURE MEAN CENTIGRADE	SOLAR RADIATION LNGLYS/DAY	RELATIVE HUMIDITY PER CENT	WINDRUN KM/DAY	RAIN FALL MM	PAN EVAPORATION MM
FEB 10	26.3	19.8	23.1	251.0	90.	166.0	1.2	2.8
FEB 11	26.2	19.5	22.9	330.0	78.	57.5	0.1	2.1
FEB 12	28.4	19.8	24.1	500.0	78.	69.5	0.0	5.1
FEB 13	29.1	19.9	24.5	330.0	86.	85.0	21.3	0.9
FEB 14	27.8	20.0	23.9	289.0	92.	73.4	10.9	2.8

SUM OF PAN EVAP WEEK PRECEDING = 36.4 MM
SUM OF PAN EVAP THIS UPDATE PERIOD = 13.7 MM
SUM OF PAN EVAP NEXT WEEK = 46.0 MM
SUM OF PAN EVAP SINCE JAN 1 IS = 254.8 MM

AVERALE UPDATE PERIOD PAN EVAP = 2.7 MM
AVERAGE EXPECTED 14 DAY PAN EVAP = 6.4 MM

FLD #	HECT	SOIL TYPE	ROOT ZONE CM	TAM MM	NO STRESS MAD MM	IRRIG COEFF	CROP COEFF	FULL CANOPY DATE	NEXT HARV DATE	ST	"IRRIGATION UPDATE AND PREDICTION" DEPLTN TODATE MM	LAST IRRIG	AMOUNT APPLIED MM	#IRRIG TODATE	AMOUNT TODATE MM	NEXT IRRIG	ACCUM PRECIP LOSSES MM	ACCUM IRRIG LOSSES MM	ACCUM MOISTURE DEFICIT MM
1	30.4	SCL	91.0	110.0	55.0	1.00	0.94	FEB 21	JAN 1		0.0	FEB 4	45.0	4	180.0	FEB 21	31.4	2.9	56.4
2	26.6	SCL	51.0	69.0	34.5	1.00	0.94	FEB 21	JAN 1		0.0	FEB 4	45.0	5	225.0	FEB 22	34.3	83.1	23.2
3	14.7	LS	36.0	53.0	34.5	1.00	0.79	MAR 6	JAN 12		0.0	FEB 4	45.0	2	90.0	FEB 21	38.1	12.5	19.7
4	38.4	CL	91.0	218.0	87.2	1.00	0.68	MAR 16	JAN 20		0.0	JAN 17	60.0	0	0.0	FEB 27	11.5	0.0	0.0
5	43.2	CL	51.0	82.0	32.8	1.00	0.60	MAR 25	JAN 27		0.0	JAN 30	60.0	1	60.0	FEB 22	44.2	4.3	22.4
6	30.4	SCL	91.0	110.0	55.0	0.85	1.00	AUG 7	MAY 1		0.0	FEB 3	45.0	26	1170.0	FEB 21	220.8	40.7	25.4
7	26.6	SCL	51.0	69.0	34.5	0.85	1.00	AUG 7	MAY 1		0.0	FEB 4	45.0	26	1170.0	FEB 22	264.6	150.6	102.3
8	14.7	LS	36.0	53.0	34.5	0.85	1.00	AUG 20	MAY 12		0.0	FEB 9	45.0	23	1035.0	FEB 22	270.3	127.1	156.7
9	38.4	CL	91.0	218.0	87.2	0.85	1.00	AUG 28	MAY 20		0.0	JAN 29	60.0	18	1080.0	FEB 24	181.1	16.3	27.5
10	43.2	CL	51.0	82.0	32.8	0.85	1.00	SEP 3	MAY 27		0.0	FEB 1	60.0	18	1080.0	FEB 24	194.1	243.5	96.5
11	30.4	SCL	91.0	110.0	55.0	0.85	1.00	OCT 29	SEP 1		0.0	FEB 3	45.0	16	720.0	FEB 21	221.4	56.4	26.1
12	26.6	SCL	51.0	69.0	34.5	0.85	1.00	OCT 29	SEP 1		0.0	FEB 1	45.0	14	630.0	FEB 22	234.6	47.6	63.5
13	14.7	LS	36.0	53.0	34.5	0.85	1.00	NOV 6	SEP 12		0.0	FEB 9	45.0	14	630.0	FEB 22	245.1	127.7	58.8
14	38.4	CL	91.0	218.0	87.2	0.85	1.00	NOV 12	SEP 20		0.0	JAN 29	60.0	9	540.0	FEB 24	156.4	17.9	28.3
15	43.2	CL	51.0	82.0	32.8	0.85	1.00	NOV 17	SEP 27		0.0	FEB 1	60.0	9	540.0	FEB 24	190.0	153.1	55.3

THE FOLLOWING FIELDS EXPERIENCED CONTROLLED
STRESS DURING THE CURRENT UPDATE PERIOD :

ALL FIELDS ADEQUATE

LAST JULIAN DAY IS 45

Irrigation Schedule Printout for the period indicated.

RHODESIA SUGAR ASSOCIATION

YEAR 1974

IRRIGATION SCHEDULING REPORT

DAILY CLIMATIC DATA FOR CURRENT UPDATE

DATE	TEMPERATURE MAX CENTIGRADE	TEMPERATURE MIN CENTIGRADE	TEMPERATURE MEAN CENTIGRADE	SOLAR RADIATION LANGLYS/DAY	RELATIVE HUMIDITY PER CENT	WINDRUN KM/DAY	RAIN FALL MM	PAN EVAPORATION MM
APR 26	23.5	14.5	19.0	217.0	89.	69.5	1.2	0.5
APR 27	23.4	16.4	19.9	255.0	84.	57.9	1.6	2.0
APR 28	22.3	15.3	18.8	234.0	93.	88.8	5.4	1.5
APR 29	20.6	16.2	18.4	197.0	95.	85.0	7.4	0.9
APR 30	22.3	15.6	19.0	187.0	90.	38.6	2.4	1.4

SUM OF PAN EVAP WEEK PRECEDING = 27.0 MM
SUM OF PAN EVAP THIS UPDATE PERIOD = 6.3 MM
SUM OF PAN EVAP NEXT WEEK = 26.2 MM
SUM OF PAN EVAP SINCE JAN 1 IS = 530.3 MM

AVERAGE UPDATE PERIOD PAN EVAP = 1.3 MM
AVERAGE EXPECTED 14 DAY PAN EVAP = 3.6 MM

FLD #	HECT	SOIL TYPE	ROOT ZONE CM	TAM MM	NO STRESS MAD MM	IRRIG COEFF	CROP COEFF	FULL CANOPY DATE	NEXT HARV ST DATE	"IRRIGATION UPDATE AND PREDICTION" DEPLTN TODATE MM	LAST IRRIG	AMOUNT APPLIED MM	#IRRIG TODATE	AMOUNT TODATE MM	NEXT IRRIG	ACCUM PRECIP LOSSES MM	ACCUM IRRIG LOSSES MM	ACCUM *CIS TLSE DEFICIT MM
1	30.4	SCL	91.0	110.0	55.0	0.85	1.00	FEB 21	JAN 1	12.2	APR 18	45.0	7	315.0	MAY 9	135.1	13.2	56.4
2	26.6	SCL	51.0	69.0	34.5	0.85	1.00	FEB 21	JAN 1	9.3	APR 18	45.0	8	360.0	MAY 11	142.9	92.8	27.4
3	14.2	LS	36.0	53.0	34.5	0.85	1.00	MAR 6	JAN 12	5.7	APR 19	45.0	5	225.0	MAY 13	158.0	24.4	29.4
4	38.4	CL	91.0	218.0	87.2	0.85	1.00	MAR 18	JAN 20	0.0	APR 22	60.0	2	120.0	MAY 17	117.5	0.8	0.0
5	43.2	CL	51.0	82.0	32.8	0.85	1.00	MAR 25	JAN 27	0.0	APR 23	60.0	3	180.0	MAY 19	144.8	35.0	31.0
6	30.4	SCL	91.0	110.0	55.0	0.60	1.00	AUG 7	MAY 1	12.2	APR 18	45.0	29	1305.0	MAY 21	323.8	51.0	25.4
7	26.6	SCL	51.0	69.0	34.5	0.60	1.00	AUG 7	MAY 1	9.3	APR 18	45.0	29	1305.0	MAY 16	372.5	161.3	106.5
8	14.2	LS	36.0	53.0	34.5	0.60	1.00	AUG 20	MAY 12	1.4	APR 20	45.0	25	1125.0	MAY 12	354.8	127.2	176.7
9	38.4	CL	91.0	218.0	87.2	0.60	1.00	AUG 28	MAY 20	0.0	APR 22	60.0	20	1200.0	MAY 17	266.6	16.9	27.5
10	43.2	CL	51.0	82.0	32.8	0.60	1.00	SEP 3	MAY 27	0.0	APR 29	60.0	20	1200.0	MAY 22	292.6	259.6	121.6
11	30.4	SCL	91.0	110.0	55.0	0.85	1.00	OCT 29	SEP 1	12.2	APR 18	45.0	19	855.0	MAY 9	324.4	66.7	26.1
12	26.6	SCL	51.0	69.0	34.5	0.85	1.00	OCT 29	SEP 1	9.3	APR 18	45.0	17	765.0	MAY 11	342.5	58.4	67.8
13	14.2	LS	36.0	53.0	34.5	0.85	1.00	NOV 6	SEP 12	5.7	APR 19	45.0	17	765.0	MAY 13	356.9	139.4	88.9
14	38.4	CL	91.0	218.0	87.2	0.85	1.00	NOV 12	SEP 20	0.0	APR 22	60.0	11	660.0	MAY 17	241.9	18.5	28.3
15	43.2	CL	51.0	82.0	32.8	0.85	1.00	NOV 17	SEP 27	0.0	APR 23	60.0	11	660.0	MAY 19	289.5	163.0	74.8

THE FOLLOWING FIELDS EXPERIENCED CONTROLLED
STRESS DURING THE CURRENT UPDATE PERIOD :

FIELD NUMBER 10 FROM APR 26

LAST JULIAN DAY IS 120

VITA

Terence L. Pearse

Candidate for the Degree of

Master of Science

Thesis: Irrigation Scheduling Program for Sugarcane

Major Field: Irrigation Science

Biographical Information:

Personal Data: Born at Niarobi, Kenya, June 2, 1942, son of Charles and Marjorie A. Pearse; married Suzanne LeBlanc Smith June 17, 1967; three children--Graeme, Keith, and Bradley.

Education: Attended elementary school in Chingola and Broken Hill, Northern Rhodesia (Zambia); graduated from Gilbert Rennie High School, Lusaka, Northern Rhodesia (Zambia) in 1960; obtained two year Diploma from Gwebi Agricultural College, Salisbury, Rhodesia in July 1963, received Bachelor of Science degree in Soils and Irrigation from Utah State University in 1975; completed requirements for the Master of Science degree, specializing in Irrigation Science, at Utah State University in 1976.

Professional Experience: 1963-1964, National Service; 1964-1966, field section manager, Hippo Valley 'Sugarcane' Estates; 1966-1969, field manager, Rhodesia Sugar Association Experiment Station; 1969-1974, irrigation research officer, RSAES, 1974-1976, studying, Utah State University.