THE USE OF CLIMATIC DATA FOR MAIZE GRAIN YIELD PREDICTIONS

by

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ABSTRACT

The development and testing of a mathematical model for maize grain yield predictions is described. The model is based upon daily considerations of soil moisture, atmospheric evaporative demand and stage of crop development.

Final yield predictions depend upon a knowledge of yield decrement due to moisture stress and the number of occasions that stress is recorded. This information was determined in the following manner:-

(i) Stress imposed in lysimeters before and after anthesis was found to reduce grain yields by 3,2% and 4,2% per stress day respectively.

(ii) A stress day was identified with the aid of mass-measuring lysimeters and a U.S. Weather Bureau Class A evaporation pan for measuring atmospheric evaporative demand. A nomogram constructed in terms of evaporative demand and available soil moisture, which discriminates between stress and non-stress days, was obtained for the Doveton soil used in the lysimeters.

The model was applied to Cedara rainfall and evaporation data and yield probability patterns for three planting dates were obtained. It was found that highest yields (8,5 Mg ha^{-1}) and least seasonal yield variation, may be expected from the earliest planting date (15/10).

The Cedara : Doveton yield prediction model was also applied to climatic records for two other Natal stations (Estcourt and Newcastle), and six stations outside Natal (Bethlehem, Potchefstroom, Hoopstad, Standerton, Ermelo and Krugersdorp). Interesting comparison of the suitability of their respective climates for maize production was obtained.

A method which uses the predicted number of stress days and the resultant yield decrement to determine the most effective and economic irrigation scheduling is developed and described.

The effect of moisture holding characteristics of various soils upon the shape of the discriminating curve is discussed, and a method of obtaining discriminating curves for other soils by modifying the Doveton curve is described.

INTRODUCTION

Farmers are often inclined to confuse the occasional good season with the norm, thereby not recognizing that they may be in an area unsuited for maize production, where recurrent inclement seasons make economic production of maize hazardous. Attempted production, however, frequently continues with the ultimate and inevitable prospect of erosion and financial failure.

In order to apply economically sound long term planning in maize production, a method must be found to predict the probability of obtaining grain yields between selected limits in given regions. If optimum use is to be made of agricultural resources then this problem deserves urgent attention. Apart from enabling the delimitation of areas according to drought risk, the ability to predict yield probability levels will simplify decision making regarding maximum fertilizer application rates, and the advisability of irrigation.

The need for a reliable method of yield prediction is emphasized by the findings of the Marais Commission's Inquiry into Agriculture (1970) which voices serious concern regarding the unbalanced development of farming systems in the summer rainfall areas of South Africa where, for various reasons, overemphasis is placed upon the production of maize. The Commission suggested further, that unsuitable areas should be withdrawn from maize production and allowed to revert to natural grazing. The method of identifying unsuitable land is, however, not described.

The main factors which affect crop performance are technology, physical properties of soils and weather. The level of technology adopted is dependent upon the farmer, while the soil's physical properties remain constant for a particular site. Weather, however, changes from season to season. It follows therefore that seasonal yield fluctuations are attributable almost entirely to weather variability.

Study of the averages of individual climatic elements over long periods of time, together with knowledge of soil type, give approximations of the cropping potential of areas. The empirical methods of classifying climate as proposed by Klages (1942) and Thornthwaite (1948 & 1954) are examples of this, but none of these methods provides accurate predictions of yield.

The most important elements of weather that influence crop performance are the supply of radiant energy and moisture. The amount of radiant energy available at the earth's surface varies according to time of year, altitude and latitude. Superimposed upon these determining factors which are constant for a given location, are short-term variations induced by changing cloud cover, humidity and advection. Besides influencing photosynthetic rate, energy supply, together with windspeed and humidity, determines the evaporative demand of the atmosphere. Moisture supply derives from rainfall. However, the mean amount, variation about this mean value, and seasonal distribution of precipitation vary markedly from place to place.

Photosynthesis and carbohydrate production in plants can only proceed while turgor in the plant tissue is maintained. Should moisture stress occur, photosynthesis is interrupted and the growth process is checked {Denmead & Shaw (1960), Vaadia, Raney & Hagen (1961), Shaw & Laing (1966) and de Jager (1968)} until turgor is restored by the removal of moisture stress.

Denmead (1961) showed that the soil moisture content at which plants wilt in the field is not constant, but depends upon prevailing weather conditions and soil type. Under conditions of low atmospheric evaporative demand plants maintain turgor at soil moisture levels that would prove inadequate when evaporative demand rises.

Should an estimate of seasonal yield be required, the day to day interaction between evaporative demand and available soil moisture (ASM) must be investigated. Such an investigation could best be carried out using a mathematical model which accounts for all the individual processes involved.

Dale (1968) reports a study for regional planning purposes where the interaction upon a maize crop of potential evapotranspiration, soil moisture, and the ease with which available soil moisture can be extracted was examined. He determined the number of days without stress in a 63-day phenological period from six weeks before silking to three weeks after silking for four locations in Iowa. Potential yields were dependant upon the number of days without stress in this period. He found that although farmers' yields were strongly affected by weather-technology interactions, there was some indication of decreasing farm yields with increasing probability of unfavourable weather, and stronger evidence of increasing coefficients of variability with increasing chances of unfavourable weather.

In this thesis an analytical approach involving the complex weather - crop growth interaction is attempted, and a mathematical model is developed and applied to the prediction of maize yields. Development of the model was carried out in two main steps:-

1. the determination of the decrease in yield per unit stress, both at different growth stages and as a function of duration of stress, and
2. the identification of a stress day as defined in terms of the interaction between atmospheric evaporative demand and available soil moisture.

Once this information is available it becomes possible to process past weather records and determine the timing and number of stress days that occur in a given season. The yield decrement due to stress can then be determined for the season.

The model was applied to past Cedara climatic data, enabling the establishment of yield probability patterns.

Weather records for a number of other stations were processed, making possible a comparison of the suitability of their respective climates for maize production. The effect of the moisture holding characteristics of various soil types, as well as the choice of different planting dates was also examined to illustrate their influence upon yield. The influence of climate upon effective irrigation scheduling was also investigated.

CHAPTER 1

EFFECT OF A MOISTURE STRESS DAY UPON MAIZE PERFORMANCE

The first step in the construction of a mathematical model for predicting crop yields is the determination of the decrement in yield due to moisture stress. This will now be discussed.

INTRODUCTION

Soil moisture supplies play a major role in determining the size of the South African maize crop. In 1966/67, which was a relatively dry season, the total yield was 5 056 000 Mg while 1967/68, which was favourably endowed with rain yielded 9 762 000 Mg of maize grain.

It has been found that moisture stress at different stages during the growth cycle of the maize plant causes yield reductions which are related to the length, timing and severity of the disturbance. Loomis (1934) reported that once seedlings emerge only limited soil moisture is required for the slow growth that takes place. He found that low moisture supplies check growth, but stimulate root penetration so that the plants seem better able to withstand subsequent dry weather because of their more extensive root systems. Salter & Goode (1967) report Russian workers as stating that drought during the early vegetative stage has little if any effect upon final maize grain yields.

Smith (1914) published results showing that the ten day period immediately following flowering is most critical with regard to rainfall. This period centering around tasseling and silking was found by Miller & Dudley (1925), Robb (1934), Wallace & Bressman (1937), Davis & Pallesen (1940), Houseman & Davis (1942), Robins & Domingo (1953) and Denmead & Shaw (1960) to be the most sensitive to moisture stress.

Tanner & Lemon (1962) deduced that since this period of maximum moisture sensitivity corresponds exactly with the period of maximum energy supply, maximum leaf area and maximum transpiration, the serious consequences of moisture stress found then are to be expected.

Denmead & Shaw (1960) found that stress during the vegetative stage delays enlargement of plant parts and although plants can recover fully once moisture is administered, the reduced plant size is accompanied by a lower final dry matter and grain yield. Stress applied during ear filling has a more direct effect upon yield because it reduces assimilation during the critical period when daily assimilation rates are normally high and when most of the assimilates are being used for grain production.

There is disagreement in the literature regarding the magnitude of the reduction in yield due to stress. This could possibly be explained by the different methods of imposing stress and different definitions of stress used.

Percentage of possible grain yield reduction per stress day			
Growth Stage	Researchers		
	Denmead & Shaw (1960) %	Robins & Domingo (1953) %	Wilson (1968) %
Late Vegetative	3-4		2
Flowering	6-8	6-8	2-3
Ear filling	2	3	5-6

TABLE 1 Reported effects of a stress day upon maize grain yields

Variety is also important as short season types might be expected to be more sensitive to a single stress day than long season types. Climatic and seasonal differences could also be responsible for some of the reported discrepancies.

Results reported by different workers are given in Table 1.

Although the work of Denmead & Shaw (1960) and Robins & Domingo (1953) yielded similar values, those of Wilson (1968) differ somewhat from the former two.

The object of the work reported now was to investigate the effect of moisture stress upon grain yield, leaf area and plant height. Particular interest was vested in the effect of stress upon grain yield as this information was required to build the model for prediction of yields.

MATERIALS AND METHODS

The effect upon maize grain yield of a day of moisture stress was determined in cylindrical containers, the problem being approached in a manner similar to that used by Denmead & Shaw (1960). The small drums used in this technique ensure uniform distribution of roots throughout the soil and even moisture removal from the entire soil profile is assumed. Examination of root proliferation after the growing season, showed an homogeneous distribution throughout the entire depth of the pots.

The containers used were non-draining steel drums 0,46 m in diameter and 0,70 m deep. They were buried in the soil with their rims 0,05 m above ground level. An aluminium neutron probe access tube, protruding 0,10 m above soil surface was placed in the centre of each container. Each drum was filled with 128 kg of soil which had been thoroughly mixed with the equivalent of 1000 kg ha^{-1} fertilizer mixture 2-3-4 (24). The maize hybrid S.A. 60 was planted in hills of three seeds each 0,305 m apart in each container. The seedlings were thinned to one per hill when 0,15 m tall. The row of pots lay precisely between two rows of plants in a field of maize also with plants 0,305 m apart. The row spacing was 0,914 m, so that the plants in the containers formed part of the uniformly spaced maize population in the field. With the planting dates used, S.A. 60 normally takes approximately 145 days to mature at Cedara. A very strict pest control schedule was adhered to.

The soil in the pots was held at above 70% available soil moisture at all times and a neutron probe was used to monitor moisture fluctuations. In hot weather, wilting could be induced within four days, suggesting uniform moisture removal throughout the drum with little chance of water collecting at the bottom of the containers.

The containers were filled with soil to 0,01 m below the rim and left open during the early part of the season. This made watering a slow and laborious process but permitted excessive rainfall to overflow. About a week before stress was due to be imposed, covers were tailored from black polyethylene sheeting and fastened around the access tube and the plant stem with plastic adhesive tape. The skirt of the plastic cover was secured around the rim of the container with binder twine. Once the stress treatment had run its course, the covers were removed completely. The installation of the pots is illustrated in Plate 1.

Three separate experiments were carried out. The treatments imposed in two were 0, 2, 4, 6 and 8 days of stress applied during the late vegetative and ear filling stages respectively. In the third experiment only the ear filling stage was investigated. Starting 10 days after silking, four-day stress periods were introduced in each of four

1a Pots lined up in trench prior to filling

1b Filled pots showing probe tubes

1c Plants growing in pots

Plate 1a, b & c Installation of pots in the field consecutive ten-day intervals. In all three experiments, randomised block designs with five treatments and five blocks were used. One pot containing two plants was considered to be a plot.

Non-destructive leaf area determinations were made in the field by measuring leaf length (L) and maximum width (W). Leaf area was calculated by summing the products (L X W) for each leaf of a plant and multiplying the total by 0,78 $\{$Leaf Area = 0,78 $\sum$(L X W)$\}$. McKee (1964) using ten different hybrids obtained a factor of 0,73 but a closer approximation of leaf areas measured, using a planimeter, was obtained at Cedara using a factor of 0,78. Hunter, Kannenberg & Gamble (1970) found a factor of 0,75 to be more suitable at Guelph.

Moisture stress day

Although this experiment was conducted in containers where stress induction was rapid and complete, extrapolation of the results obtained, to conditions in the field is justified considering the sensitivity and rapid reaction of the photosynthetic process to stress.

The curve illustrated in figure 1 after Downey (1971), illustrates the narrowness of the turgor pressure field over which photosynthetic shut-down occurs. Further, from the work of Shinn & Lemon (1968) and Barnes & Woolley (1969) it can be inferred that the maize plant is under stress when the relative turgidity of an upper leaf is below 90%. Even under field conditions therefore the shut-down of

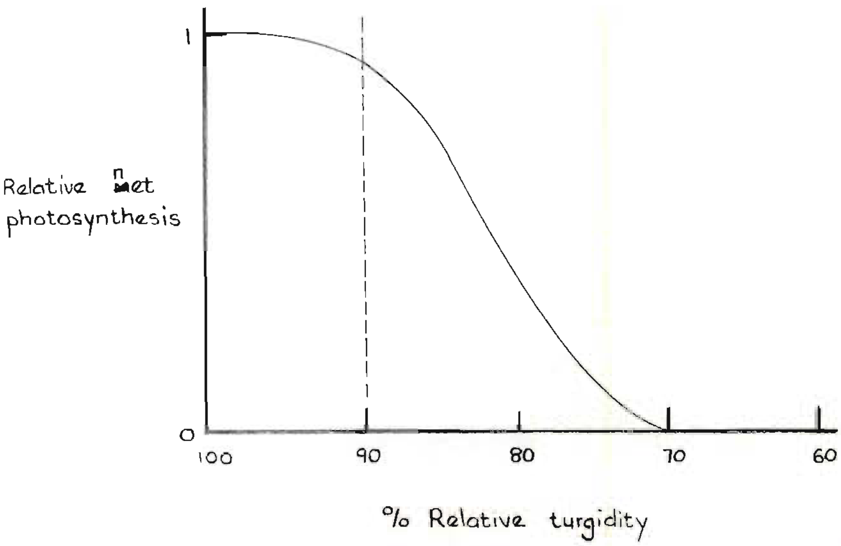

Fig. 1   Diagram of relationship between photosynthesis and relative turgidity (after Downey 1971)

photosynthetic processes approximates a step function once turgor drops below 90%.

In the container experiment a moisture stress day was deemed to have occurred when visible wilting of all the leaves on a plant occurred from 10.30 through 16.00 h. Induction and identification of this condition was simple and it was not considered necessary to determine the relative turgidity of the leaves.

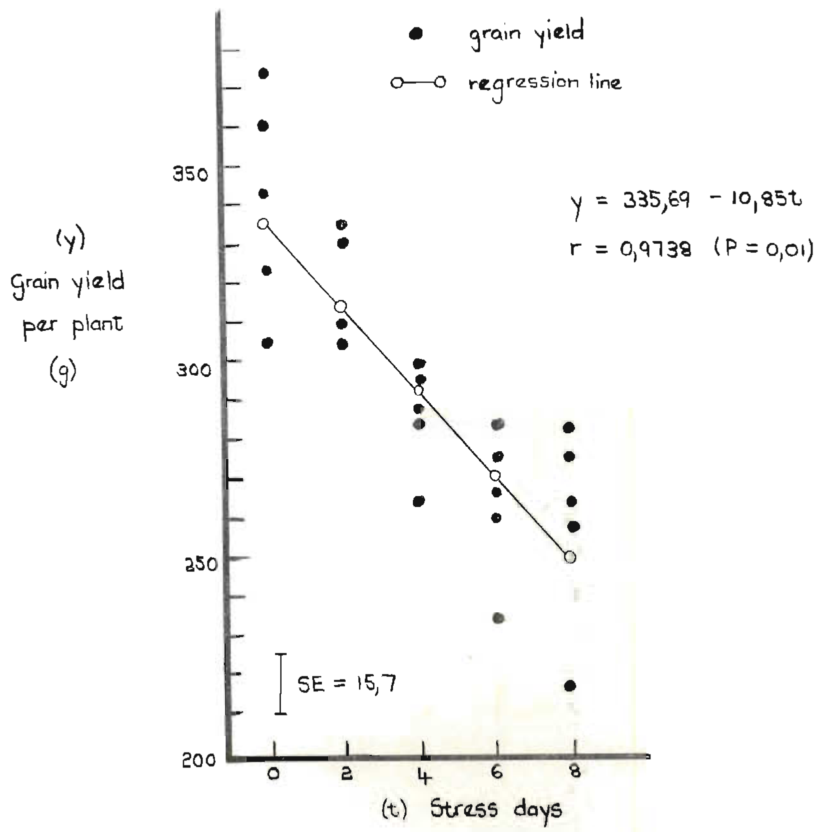

Fig. 2 Grain yield per plant as affected by moisture stress before silking.

RESULTS AND DISCUSSION

Effect of moisture stress before silking upon grain yield, leaf area and plant height. (Stress treatments commenced three weeks before silking).

Grain yield per plant, leaf area and plant height were found to decrease linearly with the number of moisture stress days between 0 and 8. As can be seen from figures 2, 3 and 4 data yielded significant regression coefficients.

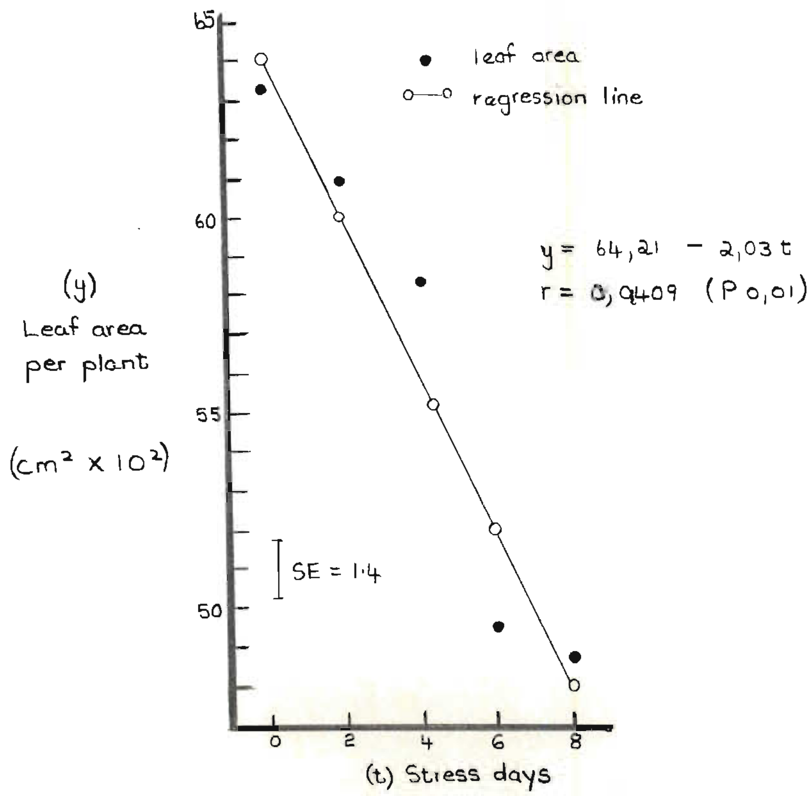

Fig. 3 Leaf area per plant as affected by moisture stress before silking.

Grain yield per plant was reduced by 3,23%** ± 0,43%, leaf area by 3,16%** ± 0,48% and plant height by 2,77%** ± 0,43% per stress day. The rate of grain reduction 3,23% per stress day agrees well with the value (3-4%) obtained by Denmead & Shaw (1960).

In addition to the observed effect of stress upon the

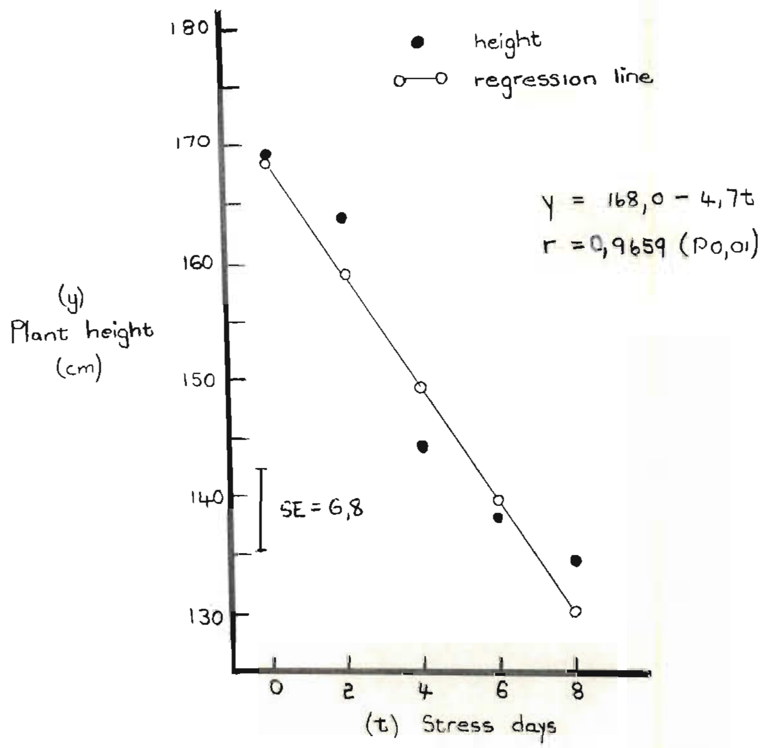

Fig. 4 Plant height as affected by moisture stress before silking.

morphology of the plant, it was noted that although stress appeared to have little effect upon the date of tasselling, the severest stress treatments caused silking to be delayed by from six to eight days. As a precaution against poor pollination, hand pollination was super-imposed upon the natural process. Du Plessis & Dijkhuis (1967) found that unfavourable moisture regimes before flowering caused the time lapse between pollen shed and silking to be lengthened. They used this relationship to predict yields.

Although plant height might not be expected to have a marked effect upon grain yield, reduction in leaf area could be important because of the resultant reduced assimilatory surface. The reduction in leaf area observed in this experiment would appear to be largely responsible for the observed reductions in grain yield. Leaf areas were measured 10 days after silking. The leaf area index (LAI) of the unstressed plants was 3,1. These findings are therefore in agreement with those of Hoyt & Bradfield (1962) and Eik & Hanway (1966) who found that a linear relationship exists between maize grain yields and leaf area for LAI values below 3,3.

Effect of moisture stress after silking upon grain yield

Starting approximately 20 days after silking, moisture stress treatments varying from 0 to 8 days were imposed upon maize plants growing in containers. The plants were all of uniform height, leaf area and maturity. Plotted yield data fitted a straight line as can be seen from figure 5 and grain yields were reduced by 4,09% $\pm$ 0,52% per moisture stress day; the linear regression coefficient being highly significant.

It was shown by Hanway (1962) that after silking, until maturity, dry matter accumulation in the plant takes place in the ear at a uniform rate. In the container experiment at Cedara this period was approximately 50 days.

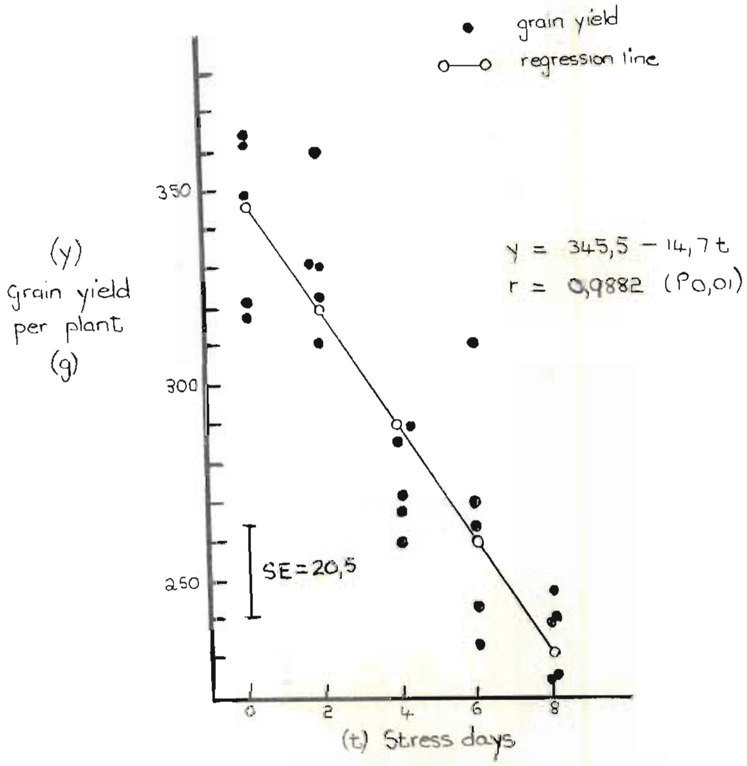

Fig. 5 Grain yields as affected by moisture stress after silking.

Yields should therefore have been reduced by 2% for each day on which assimilation was prevented. The yield reduction measured in these experiments was just lower than 4%. This high figure is due to the fact that most stress days occur when incident solar radiant energy is high, hence assimilation rate in the unwilted plants greatly exceeds the overall mean value of 2% per day which includes all cool, overcast and rainy days.

Time of stress application (No. days after silking)	Decrease in yield below control (percent decrease)
10	15,9
20	18,2
30.	16,3
40	18,0
Mean	17,2 $\pm$ 1,3

TABLE 2 The effect upon grain yield of four days of moisture stress applied at different times after silking.

In the third container experiment, four days of stress were imposed starting 10, 20, 30 or 40 days after silking. A control treatment where no stress was applied was also included. As can be seen from Table 2, no difference between the stress treatments could be measured.

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CHAPTER 2

IDENTIFICATION OF A DAY OF MOISTURE STRESS IN MAIZE AT CEDARA

In order to apply the information regarding yield reduction due to stress to past weather records, it must be possible to identify a day of moisture stress in terms of atmospheric evaporative demand and available soil moisture. How this was achieved will now be discussed.

INTRODUCTION

Veihmeyer & Hendrickson (1955) published data indicating that between field capacity and wilting point, soil moisture was equally available to plants. In this case potential transpiration rate would be maintained above wilting point. It has been found, however, that once the available soil moisture content falls appreciably, potential transpiration rate can only be maintained at low evaporative demand or for crops growing on sandy soils. Thornthwaite & Mather (1955), Makkink & van Heemst (1956), Hagan, Peterson, Upchurch & Jones (1957), Lemon, Glaser & Satterwhite (1957), Scholte Ubing (1960), Bahrani & Taylor (1961), Denmead (1961), Denmead & Shaw (1962) and Hill (1965) have published data showing that for given evaporative demands, actual transpiration rate will fall below the potential as the moisture supply decreases.

In the experiment examining the effect of a moisture stress day upon maize performance it was shown that it is possible to define a stress day and determine the loss in grain yield due to the imposition of such. In order to apply these results in practice it is necessary to be able to identify stress conditions in terms of evaporative demand and soil moisture status.

Using United States Weather Bureau Class A evaporation pan readings as a measure of the atmosphere's evaporative demand and mass-measuring lysimeters to measure the soil's moisture status, an attempt was made, under summer conditions at Cedara, to establish the sets of supply and demand which constitute moisture stress days.

MATERIALS AND METHODS

A U.S.W.B. Class A evaporation pan was situated in an open space adjacent to a field of maize at the Agricultural Research Institute, Cedara, Natal. Daily pan readings were made at 08.00 h. These readings were used as an indication of atmospheric evaporative demand.

Open pan evaporation, E_O and not potential evapotranspiration PE_T or evapotranspiration E_T was chosen for an estimate of demand, as in any yield prediction programme this observation, or an estimate thereof would be used.

Ten mass-measuring lysimeters were used to follow the daily march of soil moisture content. A trench 16 m long by 0,6 m wide, a recording station and a 9 m shunt line were constructed in a maize field. Four low platform trucks each capable of carrying four lysimeters 0,46 m in diameter and 0,70 m deep were placed on rails in the trench. The rims of the lysimeters were at ground level. The lysimeters were similar to the drums used in the experiment to determine yield decrement due to stress described in Chapter 1, and the same assumptions regarding uniform moisture removal and root proliferation were made. Definition of a stress day is as described earlier, viz. visible wilting of all leaves on a plant to occur at least from 10.30 through 16.00 h.

The maize in the field was planted in 0,914 m rows with plants 0,305 m apart. The lysimeter trench was situated precisely between two maize rows and when the trucks were touching one another the plants in the lysimeters were in one continuous row and 0,305 m apart as were the plants in the field. The plants in the lysimeters formed part of the uniformly spaced maize population in the field. A short extension line permitted each lysimeter to be brought to the recording station where it could be hoisted off the truck by block and tackle and the mass determined.

Each lysimeter was filled with 128 kg of air-dry-soil of the Doveton series (see van der Eyk, Macvicar & de Villiers 1969). Field capacity of the soil is 34% moisture by volume and wilting point is 22%. Before filling each lysimeter the equivalent of 1000 kg ha^{-1} of mixture 2-3-4 (24) was thoroughly mixed with the soil. An attempt was made to achieve the same bulk density (1200 kg m^{-3}) within the lysimeter as in the field. Each lysimeter contained two plants spaced 0,305 m apart. The hybrid S.A. 60 was used. The lysimeters, lysimeter trench, recording station and covered shunt line are illustrated in Plate 2.

The scale used for mass-measuring the lysimeters was modified

2a Lysimeters at recording station

2b Lysimeters on trucks in trench

2c Recording station and covered extension line

Plate 2a, b & c Lysimeters, trench and recording station by adding a miniature rider and beam directly beneath the existing beam as illustrated in Plate 3c.

These modifications permitted mass measurements to a resolution of ± 4,5 g. In these lysimeters 162,3 g was equivalent to a moisture loss of 1 mm. Hence changes in mass corresponding to 0,03 mm of water were measurable. The lysimeter mass determinations were made daily between 06.45 and 07.15 h.

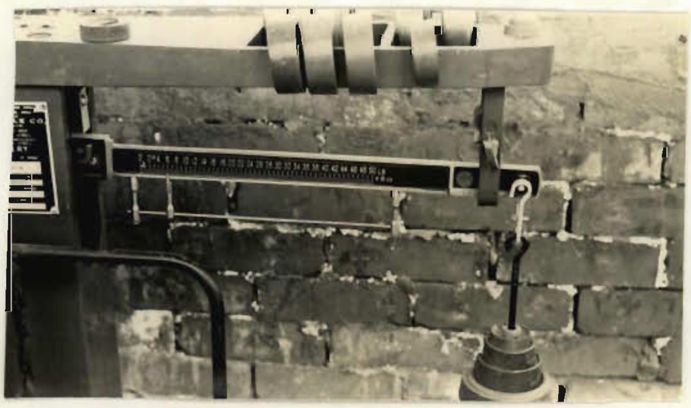
Aluminium access tubes for soil moisture determination by the neutron scatter method were placed concentrically in each lysimeter. Probe readings agreed with mass measurements but small differences were observed between lysimeters, so that each lysimeter required its own calibration curve. Use of the probe was discontinued as it proved to be less accurate and more time consuming than mass measuring. Furthermore, whereas one person could manage the mass measurements, two were required for the probe.

A shelter which could be raised as the crop developed was erected over the shunt line so that during wet weather the trucks could be rolled under cover. This shelter also prevented the crop from being damaged on the two occasions when hail fell. The shelter is illustrated in Plate 2c.

A wide range of soil moisture contents in different lysimeters was maintained at a given time. This ensured that on most days stressed and normal plants were growing under the same evaporative demand conditions. Whenever possible two lysimeters were brought to field capacity simultaneously. There was close

3a Siting of Class A pan adjacent to experimental field.

3b Interior of measuring station showing lysimeters, hoist and scale



3c Modified scale beam showing miniature rider.

Plate 3a, b & c Class A pan, inside of recording station and modified scale beam.

agreement within pairs during drying as can be seen from Figure 6.

The period from 20 days before silking to 30 days after silking was considered. Although 10 lysimeters were used in the final determinations, two additional lysimeters were placed at the open end of the trench to eliminate border effects. The leaf area indices recorded in this study were between 2,0 and 2,5. The small variation can be ascribed to the effect of the stress treatments applied.

Theory

Pan evaporation (E_O) and available soil moisture (ASM) for each day were plotted on a nomogram and stress days were differentiated from normal days using dots and crosses respectively. The empirical curve which best separates the two different sets of data (stress vs normal) is taken to be the discriminating function describing the critical conditions of supply and demand i.e., it represents the critical available moisture which will induce stress should evaporative demand be equal to or greater than the value indicated by the curve (see Fig. 7).

An empirical function discriminating between wilted and non-wilted maize plants growing under given sets of supply (ASM) and demand (E_O) can be found by plotting corresponding values of these observations for each day on a graph of E_O vs ASM and dividing the wilted from non-wilted data by a line which yields the lowest number of misclassifications. Such a curve may be determined in the following manner:

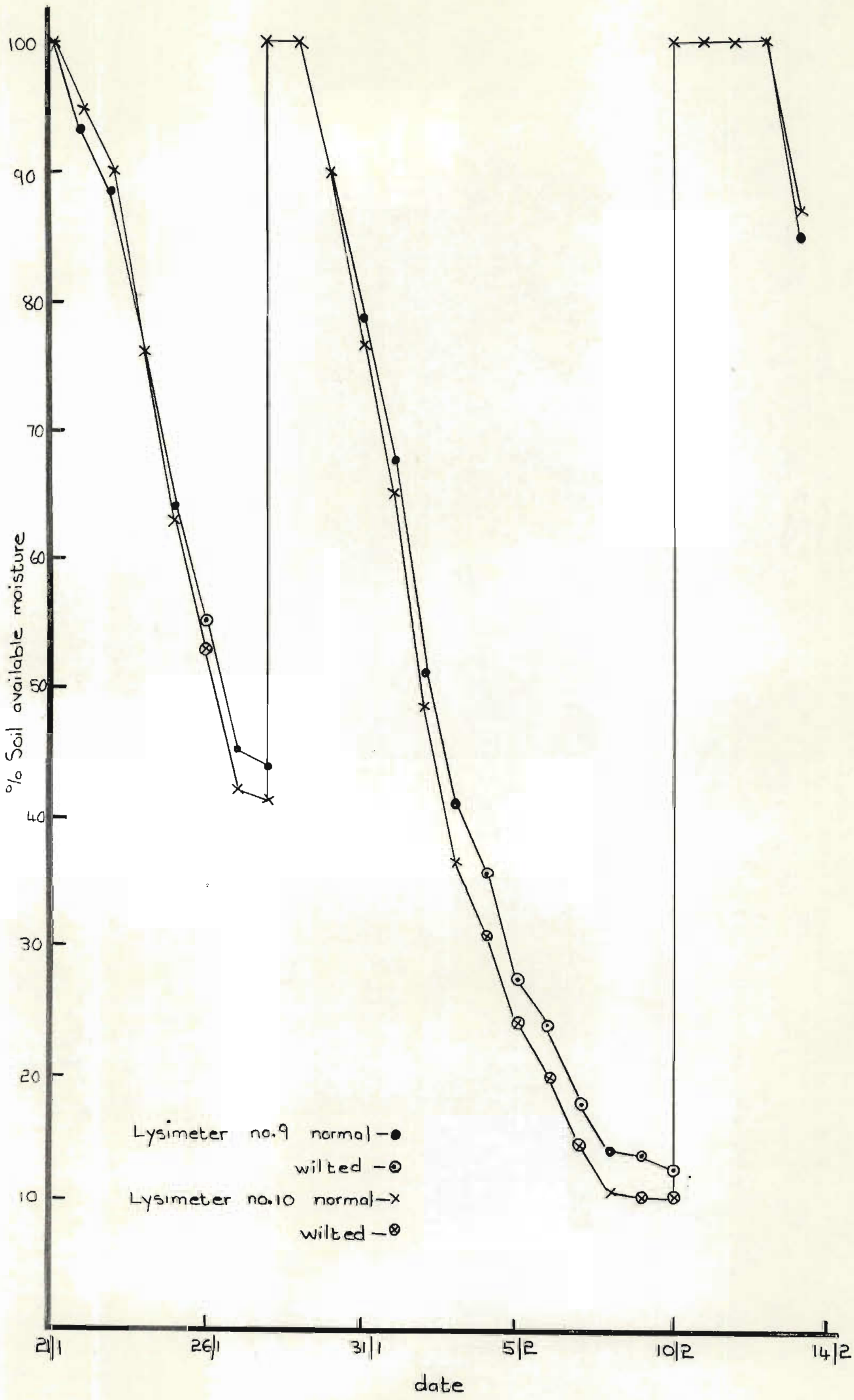


Fig. 6 An example of the daily weights of a pair of lysimeters.

If P = probability of a misclassification

M = number of plotted points falling on wrong side of line, and

N = total number of observations,

then if the subscripts N and W indicate normal and wilted conditions respectively

$$P_W = \frac{M_W}{N_W}$$

Now, for an accurate discriminator

(i) P_N and P_W must be a minimum, and

(ii) $P_N \doteq P_W$

Hence the smooth curve which best meets conditions (i) and (ii) will be the discriminating function.

RESULTS AND DISCUSSION

During the 50 day test period a total of 314 sets of lysimeter mass measurements, Class A pan recordings and state of turgor observations were obtained. Rain eliminated several day's data. During this period the maximum pan reading was 14,2 mm and the average 5,8 mm.

The data obtained consisted of two populations, the first of 120 occasions when wilting occurred and the second of 194 when turgor was maintained. The empirical discriminating function (see Fig. 7) separating these two sets of data was determined by the method discussed. This curve (Curve I) identifies a stress day for maize on a soil of the Doveton series.

A number of smooth discriminating curves were drawn separating wilted and non-wilted data. The lowest values of P_N and P_W for which $P_N \doteq P_W$ were found to be $P_N = \frac{15}{194}$ (7,7%) and

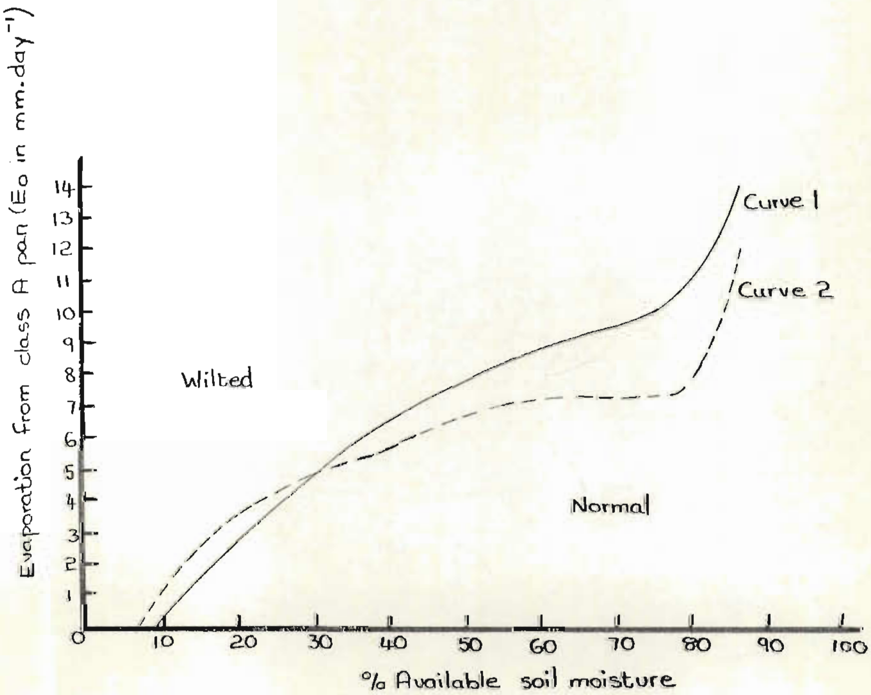


Fig. 7 Stress day discrimination curves for Cedara (Curve 1) and Iowa (Curve 2; Denmead, 1961).

$P_W = \frac{9}{120}$ (7,5%). Curve I in Fig. 7 was described according to these conditions.

The magnitude of P_N and P_W indicates that discrimination accurate to 7,6% can be applied, or for each 13 wilted days defined, one will be erroneous. It has been shown that a decrease in yield of between approximately 3 and 4% per stress day is expected, and if a total of 13 stress days were to occur in one season then the maximum error for the technique would be approximately 4%.

Denmead (1961) plotted a similar curve for maize on an Iowa Colo silty loam, but whereas in the Cedara case evaporative demand was represented by E_O Denmead (1961) used transpiration at field capacity (PE_T) in place of Class A pan evaporation. Using Penman (1956), Denmead (1961) stated that PE_T bore a relationship of 0,83 to E_O. Using this ratio it was possible to convert Denmead's (1961) data for presentation (Curve II) in Fig. 7. Close agreement with the curve for Cedara is evident. However, no adjustment for evaporation from the soil surface was possible and since this might be appreciable, particularly when available moisture is high, this could explain the difference between the curves.

In soils which exhibit a sharp increase in soil moisture tension for a given reduction in ASM, the slope of the discriminating curve will be steep, or conversely, where soil moisture is readily available over the entire range of ASM, the slope of the curve will be small. Any intermediate slope is possible depending upon the characteristics of the particular soil. Part of the differences between Curves I and II in Fig. 7 could thus be explained. The necessity for determining discriminating functions corresponding to the different soil types is emphasized by these effects.

CHAPTER 3

MODEL FOR DETERMINING MAIZE YIELD PROBABILITIES ON A DOVETON SOIL

INTRODUCTION

Soil moisture tension restrains the flow of water towards roots. This negative force increases as soil moisture content decreases (Gardner 1960). When atmospheric evaporative demand exceeds the rate at which soil can supply water against soil moisture tension, conditions of moisture stress exist in the plant and it wilts (Denmead 1961). The concomitant cessation in photosynthesis and growth results in decreased yields as demonstrated in Chapter 1.

If a model is to be constructed to predict yield probabilities, it must attempt to describe yield as a function of soil moisture content and atmospheric evaporative demand. It should consider soil and atmospheric conditions on each day of the growing season in order to determine the occurrence and number of days on which stress conditions prevail, and then, using this information estimation of the decrease in final yield due to the total number of stress days is made possible. The mathematical model for this process takes the form:-

$$Y = \frac{P(100 - \sum_n L_n)}{100} \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

where;

Y = seasonal maize grain yield (Mg ha^{-1}),

P = potential or possible seasonal grain yield (Mg ha^{-1}), and

L_n = decrement in final grain yield due to day n being a stress day (%).

The essence of constructing such a model is in the definition of a stress day in terms of atmospheric evaporative demand and soil moisture conditions, and the determination of final seasonal yield due to stress. Development of the model will be undertaken by considering these two aspects.

DECREMENT IN YIELD DUE TO STRESS

L_n, the decrement in final seasonal grain yield due to day n being a stress day was determined as described in Chapter 1 by subjecting plants to varying numbers of stress days at different stages of development and measuring the corresponding decrements in final yield. From these results Equation 1 was derived.

Before silking L_n was found to be equal to 3,2% decrease in yield per unit stress day, while after silking the figure was 4,2%. Within these two periods L_n was found to be independent of stage of development. Furthermore, L_n was unaffected by stress days occurring intermittently or continuously. No values for L_n were attained during flowering but at this stage the plant is particularly susceptible to moisture stress. The value 7% which falls within the 6 to 8% range found by both Robins & Domingo (1953) and Denmead & Shaw (1960), has been adopted. The value of L_n used in the model is thus a function of stage of development of the crop.

Stress during the early vegetative stage is reported to have little effect upon final performance {Loomis (1934) and Salter & Goode (1967)}, while Dale & Shaw (1965) (they were able to account for 81% of yield variations when considering the number of days on which no stress occurred) ignored stress which occurred earlier than 42 days before silking.

In Fig. 8 the relationship between L_n and time as used in the model is illustrated.

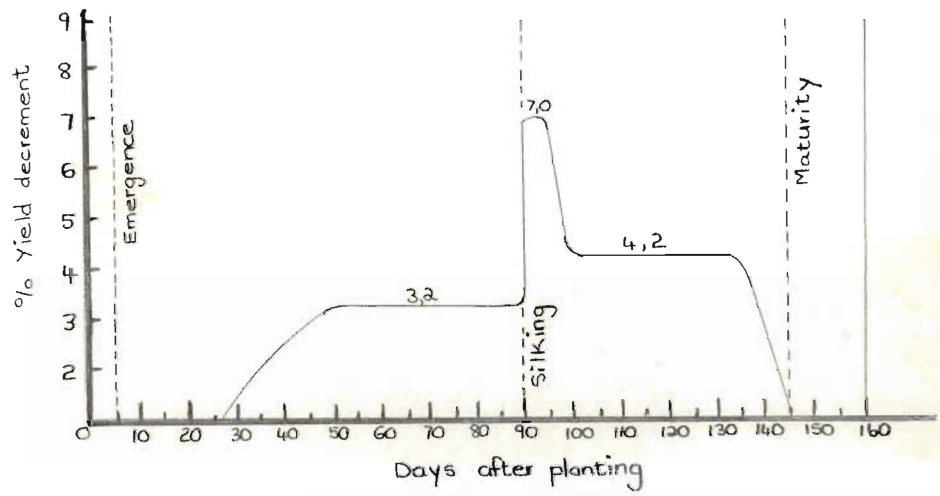


Fig. 8 Schematic diagram of relationship between age of crop and percentage yield decrement due to one day of moisture stress.

STRESS DAY

In Chapter 1 a stress day is defined as a day on which visual wilting of the leaves of the crop occurs uninterruptedly between 10.30 and 16.00 h. Such days are identified by applying the discriminating function found experimentally (see Fig. 7). Here, atmospheric evaporative demand was measured using a U.S.W.B. Class A evaporation pan and soil moisture content was determined by mass measurement. Stress days were identified by observation and the results permitted construction of the discriminating function shown in Fig. 9.

Figure 9 may be used to determine whether a day is a day of moisture stress by plotting the evaporative demand at the existing soil moisture. Should this point lie in the shaded area wilting will not occur, but should it fall on or above the discriminating function a stress day is recorded.

EVAPOTRANSPIRATION

Use of the mathematical model requires daily estimates of evapotranspiration to compute instantaneous available soil moisture. A constant relationship exists between potential evapotranspiration of maize and evaporation from a Class A pan {Denmead & Shaw (1962) and Cackett & Metelerkamp (1964)}. The value of the constant varies with the development of the crop and application of this factor permits the estimation of evapotranspiration for each day of the growing season. Denmead & Shaw (1962) obtained a maximum value for E_T/E_O of 0,82 at anthesis while Cackett & Metelerkamp (1964) obtained a value closer to 1. Both sets of workers obtained E_T/E_O curves for the growing season of essentially the same shape. In the Cedara lysimeter trial the E_T/E_O ratio, during the period centred around silking, was computed to be 0,75. A curve similar in shape to those described by Denmead & Shaw (1962) and Cackett & Metelerkamp (1964), but peaking at 0,75 was constructed for Cedara and is illustrated in Fig. 10.

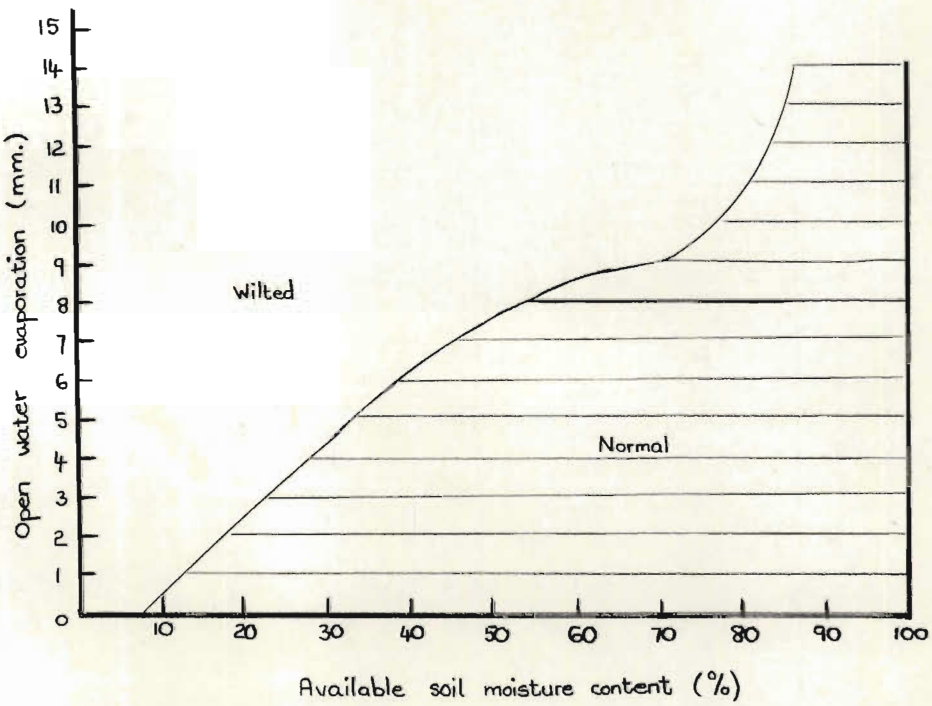


Fig. 9 Discriminating function for defining stress days in terms of atmospheric evaporative demand and soil moisture for maize growing in soil of the Doveton series.

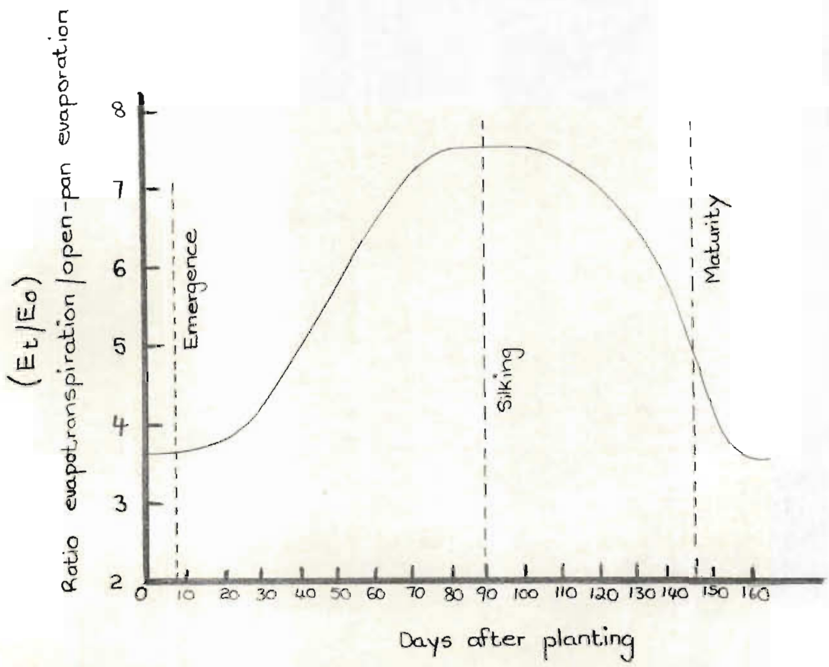


Fig. 10 Seasonal trend in E_T/E_O ratio.

AVAILABLE SOIL MOISTURE

Use of the discriminating function (Fig. 9) implies knowledge of the available soil moisture and evaporation for each day. In the present application an empirical model as proposed by Shaw (1963) was used for estimating soil moisture.

The soil was divided into several layers and the water budget of each was estimated separately. Moisture status for the entire depth is the aggregate over all layers.

Consider the n^{th} layer of the soil profile. At the end of a day the available soil water W_n, is given by:

$$W_n = WO_n + WI_n - E_n \qquad \ldots\ldots\ldots\ldots (2)$$

where;

WO_n = the available moisture in the layer at sunrise (mm),

WI_n = water flowing into the layer either from rainfall (top layer) or by percolation from above (mm), and

E_n = water extracted by the roots for use in evapotranspiration (mm).

WI_n for the surface layer is determined from recorded rainfall less runoff, with runoff being a function of rainfall and antecedent precipitation index (Shaw 1963).

The equation used to calculate the antecedent precipitation index (API) is:

$$API = P_1/d_1 + P_2/d_2 + \ldots\ldots\ldots\ldots P_i/d_i + P_O/2 \ldots\ldots\ldots\ldots (3$$

where;

P_O = precipitation on day being considered.

P_i = precipitation i days prior to P_O

d_i = i^{th} days

Shaw (1963) made use of an intermittent correction to P_O later in the season. When $P_O < 25$ mm or the top 900 mm of the soil profile was not at field capacity he put $P_O = 0$. This correction was not applied at Cedara as it did not seem to fit local conditions.

The nomogram due to Buss & Shaw (1960) as reproduced by Shaw (1963) may be used to obtain runoff from API and precipitation.

For deeper layers WI_n is the excess in W_{n-1} over field capacity for the $(n-1)^{th}$ layer from the previous day. Should WI_n be greater than field capacity only the amount of water equal to field capacity is transferred from the $(n-1)^{th}$ layer and the rest is stored.

Water movement

The percentage available moisture was calculated for each day, and in the steps required by the model. From day 1 to day 16 the entire top ~~105~~ 150 mm of soil was considered and during this period the water loss was assumed to be 2,5 mm per day with meteorological conditions being ignored. During this period the plants are small and contribute little towards E_T so that conditions are analogous to bare soil, with short term evaporative losses not normally being suffered at depths greater than 150 mm. After day 16 when roots progressed beyond 150 mm the full model functioned but if stress conditions were encountered before day 29 those were ignored.

The model reviewed the soil moisture situation at sunrise each day. Water movement through the soil was considered layer by layer, with each layer or zone 300 mm deep, which is the depth evacuated by gravitational water in one day. When excess water (WI) entered a zone from above it was added to available water (WO) already in the zone and the total was available to plants for the next 24 hours regardless of whether this total exceeds field capacity (f.c.) for the zone.

The model furthermore assured for layer n, that;

i If $WI_n + WO_n >$ f.c. then excess of f.c. was available for percolation after 24 hrs,

ii If $WI_n + WO_n >$ 2 f.c. then an amount equal to f.c. was available for percolation after 24 hrs, and

iii If $WI_n + WO_n <$ f.c. no percolation from zone n would take place.

If insufficient moisture was available (to supply E_n) the excess requirement stored for each layer was tapped, starting from the top and moving down layer by layer. This assumes moisture removal to be transferred from a dry layer to the upper layers first.

If a stress day occcurred it was assumed that no evapotranspiration took place and all initial moisture was returned to each layer.

Root distribution

A daily adjustment for root distribution was necessary because of increased volume of soil and consequently moisture available each day due to root proliferation. Cackett & Metelerkamp (1964) found root elongation rate to be linear up to the maximum depth reached at anthesis. Similar observations were made on a Doveton soil at Cedara. The root volume-depth pattern found at Cedara bares favourable comparison with the published findings of Weaver (1926), Fehrenbacher & Alexander (1958) and Shaw (1963). Separate moisture extraction patterns were established for each day of the growing season and several of these are illustrated in Fig. 11.

Once evapotranspiration had been determined from the E_T/E_O curve in Fig. 10, it was necessary to find the proportion of moisture extracted from the different layers. Before anthesis while the roots are growing downwards, the entire stored water reserve in any zone was only considered available to the plants once the roots had passed right through the layer. While only a portion of a zone was penetrated by roots the amount of stored water in that zone considered available to the plant was taken to

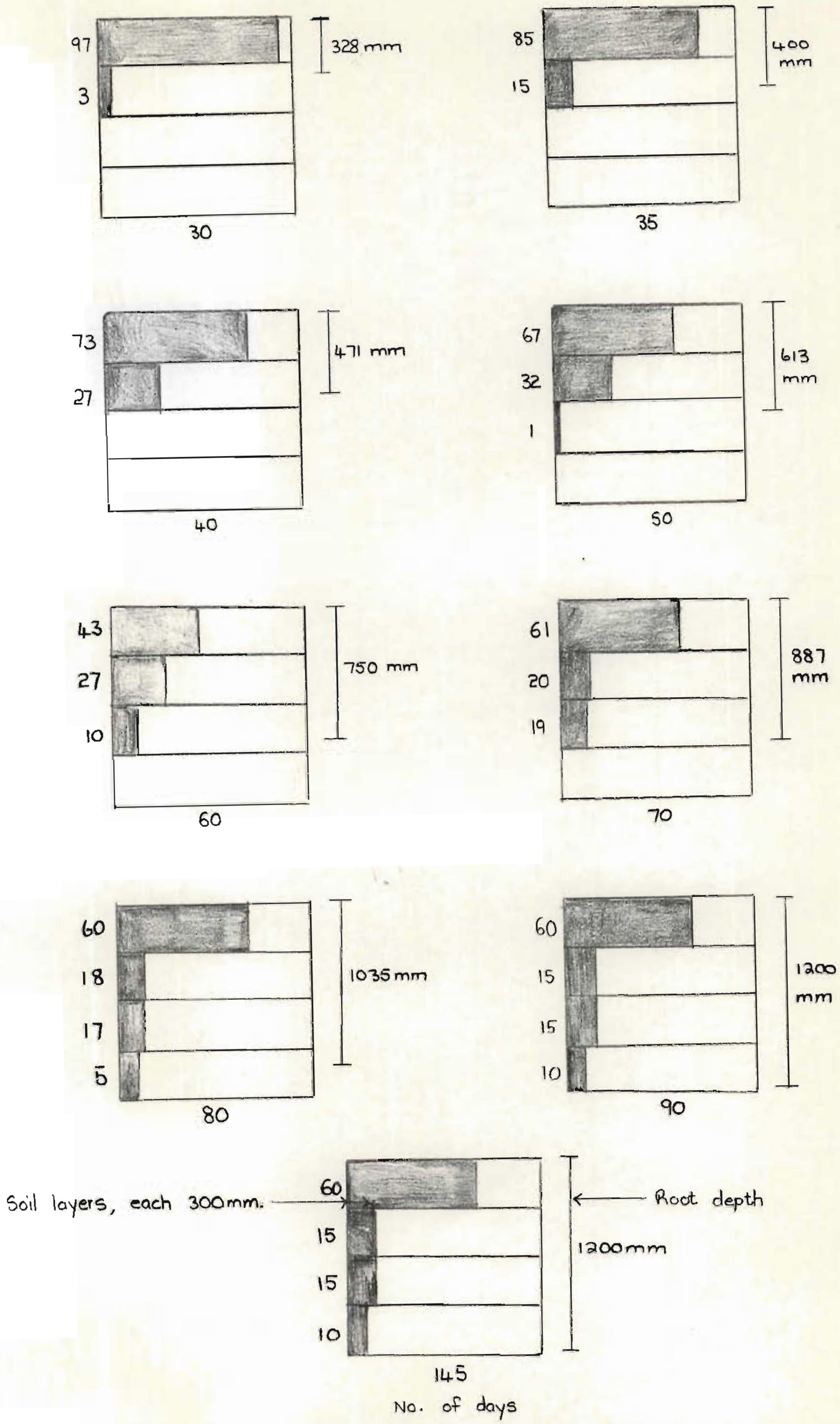


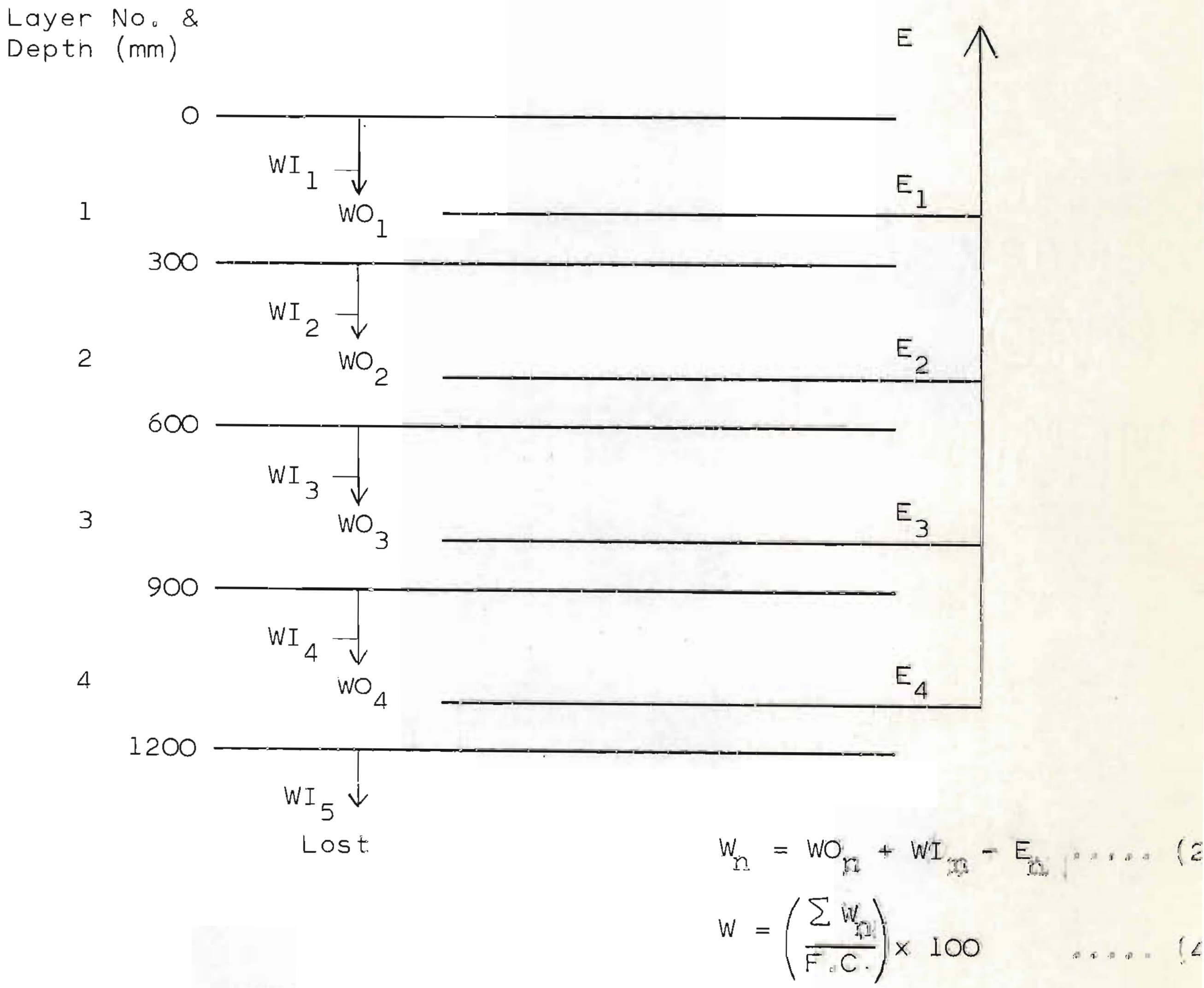
Fig. 11 Models for determining proportion of moisture loss extracted from each soil layer.

be directly proportional to the distance penetrated into that zone by the roots.

E_n was therefore calculated from the estimation of evapotranspiration combined with factors adjusting for root distribution in the soil. The value of W (percentage of total soil moisture) for use in Fig. 9 is:

$$W = \frac{\sum W_n}{\text{Field Capacity}} \times 100 \qquad \ldots\ldots\ldots (4)$$

A graphic illustration of the model for estimating W is presented in Fig. 12.



WI_1 = Rain - Runoff

$WI_{2 \text{ to } 5}$ = Percolate from upper layer in excess of its field capacity

WO_n = Available moisture in layer n at sunrise

E = Evapotranspiration. E_n is a function of root distribution pattern and time.

FIG. 12 Model for estimating daily percentage of total available soil moisture.

Water holding characteristics of a Doveton soil

The water holding characteristics and rooting pattern which occur in a Doveton soil are used in the model. As maize roots normally penetrate to 1200 mm in this soil, only the water holding characteristics of this depth are considered. The moisture holding characteristics of various depth zones were determined with pressure plate apparatus as well as gravimetrically using undisturbed cores taken in the field. These values are presented in Table 3.

Depth zone mm	Bulk density g/ml	Wilting point (%)[1] 15 Bar	Field capacity (%)[1] 0,3 Bar	Available soil moisture (%)[1]	(mm)
0-300	1,266	26	32	6	22,8
300-600	1,129	23	35	12	40,6
600-900	1,368	19	29	10	41,0
900-1200	1,397	24	32	8	33,5

[1]Percentage of dry mass.

TABLE 3 Moisture holding characteristics of a Doveton soil.

PROCEDURE FOR EXECUTION OF MODEL

Computation was executed on the I.B.M. 1130 computer. Each day of the growing season was considered starting from 1st November as planting date.

After determining the percentage of the total available moisture (W) within the root zone, the critical soil moisture (CASM) corresponding to recorded atmospheric evaporative demand for that day was extracted from the discriminating curve and compared with W. A stress day was identified if W $\leq$ CASM.

The dates of stress days were recorded and their corresponding L_n values determined. The total of all L_n values gave the percentage yield decrement due to stress. An estimate of seasonal yield was then made by applying Equation 1.

A schematic representation of the steps used in the computer programme is given in Fig. 13. The complete computer programme is listed in the Appendix.

1 Infiltration

2 Water budget for each layer

3 Adjust for water deficit
Total water in n layers - ASM (mm)
Determine f.c. in root zone
Determine ASM (%)

4 Determine CASM
Compare ASM and CASM

If ASM < CASM → Record stress day and date. Return moisture status to initial

If ASM > CASM → Repeat for next day

Fig. 13 Schematic representation of steps used in computer programme.

CONCLUSIONS

A mathematical model which may be used to determine frequency distribution of yield from climatic records was developed. The longer the period covered by the data considered the more accurate will be the predictions of probabilities of obtaining grain yields between selected limits.

The usefulness of the model results from its application to past weather conditions for, if the number of stress days which occurred over the past twenty years, say, are determined and it is assumed that the average weather over the next 20 years will be the same as that over the past 20 years, an estimate of the drought risk and hence expected yield may be obtained. This type of estimate is called a climatological prediction.

CHAPTER 4

APPLICATION OF MODEL

CEDARA

The model expounded in Chapter 3 applies to a Doveton soil since the soil's water holding characteristics and the plant's rooting pattern apply specifically to this soil. The Doveton is a clay laom which holds 138 mm of available moisture in the top 1200 mm. The application of the model to other soil types will be discussed later.

The climate of Cedara is similar to that of the major maize growing areas of South Africa in that it can be classified as mesothermal or steppe, having a distinct period of summer rain with dry winters. Cedara rainfall and temperature means calculated for 50 years of data are presented in Table 4.

Cedara $29^{o}32'$ S $30^{o}17'$ E Alt 1076 M

	MONTH												TOTAL
	J	A	S	O	N	D	J	F	M	A	M	J	
Rain-fall	15,7	24,0	44,2	81,6	111,6	128,8	122,8	136,8	155,6	52,8	30,7	15,4	880,0
Rain Days	4	6	10	16	18	21	19	17	17	11	6	4	149
Max. Temp ^{o}C	19,0	21,5	22,7	23,0	23,6	24,7	24,9	24,9	24,0	22,8	21,0	19,1	
Min. Temp ^{o}C	4,2	6,8	8,6	10,6	12,1	13,4	14,3	14,5	13,5	11,0	7,4	4,5	
Mean Temp ^{o}C	11,6	14,1	15,7	16,8	17,9	19,1	19,6	19,7	18,7	16,9	14,2	11,8	

TABLE 4 Mean monthly rainfall and mean number of rain days, mean temperature and mean daily maximum and minimum temperature for given months for Cedara.

Expected yields for Cedara

Class A pan records were available for Cedara for a period of 12 years starting with the 1959-60 season. The yield probability model was tested over the entire 12 year period with calculations carried out for each day of each growing season. The potential or possible yield P was taken as 10,0 Mg of grain per hectare which is based upon present day estimates for better than average levels of technology.

When making climatological predictions it is important to know the chance of occurrence of particular yields. This information is best obtained from histograms of the probability of occurrence of yields between selected limits. The Cedara predictions are therefore compiled and presented in this form in Fig. 14.

The histogram indicates that at Cedara the probable average yield is 7,9 Mg ha^{-1} while a yield of between 8 and 10 Mg ha^{-1} can be expected in just better than one out of two seasons. The chances of getting yields between 6 and 8 Mg ha^{-1} are one in four, and just less than one in five for yields between 4 and 6 Mg ha^{-1}. It is unlikely that yields below 4 Mg ha^{-1} will occur.

Test of results

Table 5 presents the predicted yields together with subjective ratings for the actual seasons. The ratings were obtained from a perusal of the results of several maize trials at Cedara. As hybrids, fertilizer rates, planting dates and plant populations varied from trial to trial and season to season, a rating is the only basis on which comparisons can be made. Furthermore,

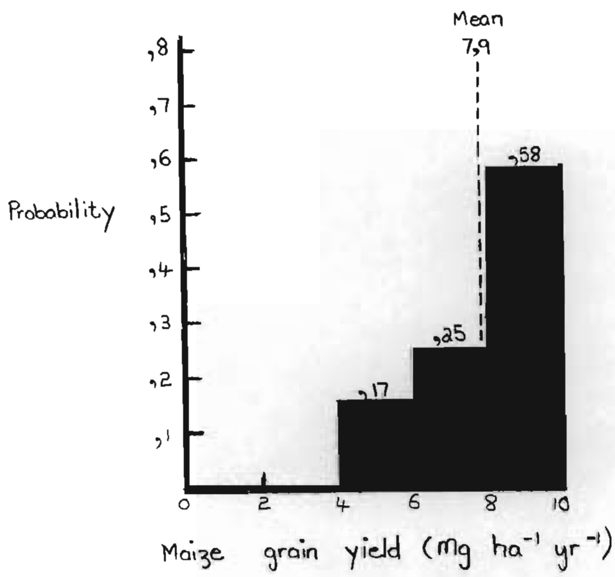


Fig. 14 Histogram of probability of occurrence of seasonal maize yields between selected limits at Cedara.

technology has made spectacular advances during the past 12 years, so that a high yield in 1959/60 is considered relatively poor today.

Although the comparisons are not conclusive a fair correlation between yield and rating seems to exist.

Planting date and its effect upon yield probabilities

In its original form the model used was constructed for the prediction of grain yields when planting date was 1/11.

Season	Predicted Yield (Mg ha^{-1})	Season Rating
1959/60	6,49	Fair
1960/61	8,49	Good
1961/62	10,00	Good
1962/63	9,39	Good
1963/64	5,21	Fair
1964/65	7,02	Poor
1965/66	6,97	Fair
1966/67	9,34	Good
1967/68	9,07	Fair
1968/69	5,54	Poor
1969/70	8,42	Good
1970/71	9,30	Good

TABLE 5 Predicted maize grain yields and season rating for Cedara.

Trials and experience at Cedara indicate that better yields are generally obtained from early plantings. It was therefore decided to test the effect of early planting by re-running the programme using 15/10 and 15/11 as planting dates. Yield probability histograms for each planting date are presented in Fig. 15.

From the three histograms presented in Fig. 15 it is evident that predicted mean yield decreased while seasonal yield variation increased as planting date was delayed. Thus, for better and more reliable yields early planting is indicated.

Temporal variations in stress periods

Certain physiological growth stages of the maize plant are more sensitive to moisture stress than others. For example, yield is seriously decreased by drought which occurs during anthesis (see Fig. 8). If a known time distribution pattern of drought probability exists for a given place, this will

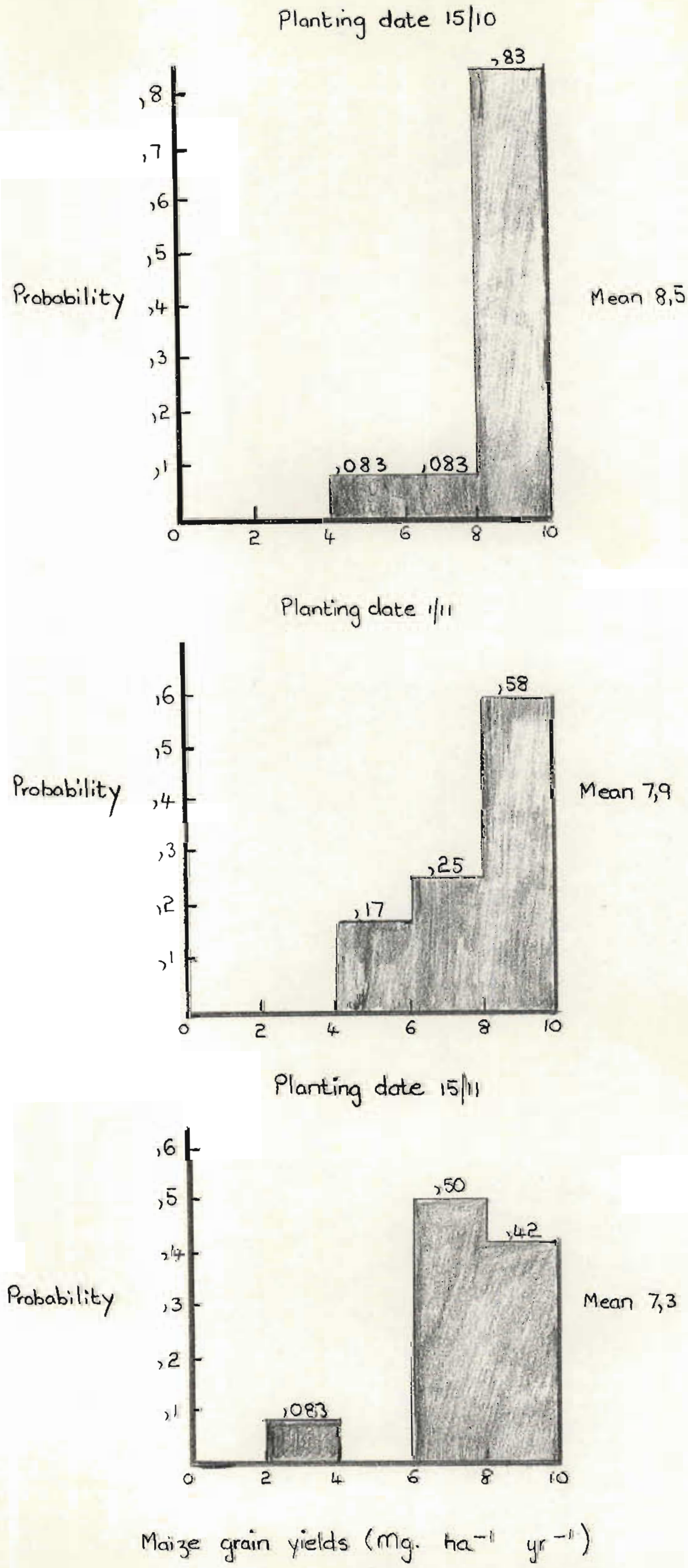


Fig. 15. Histograms of probability of occurrence of seasonal maize yields between selected limits for three planting dates at Cedara.

greatly assist farm planning, as now planners, using this knowledge can select suited hybrids and planting dates which will improve yields. It was therefore decided to investigate the distribution of stress days throughout the growing season.

Fig. 15 indicates that early planting is advisable hence this principle should be accepted. Next, periods of high moisture stress were sought in order to obtain information regarding most suitable germination-to-anthesis and anthesis -to-maturity periods. The growing season was divided into 29 pentades and stress probabilities determined for each. Histograms depicting stress probability with respect to time, for each of the three planting dates are illustrated in Figs. 16a, b & c. From Fig. 16a it can be seen that least stress (3,75 days yr^{-1}) may be expected from early planting, with no obvious stress vs time pattern being apparent. The probability of expected stress increases to 5,75 days yr^{-1} when planting is delayed until 1/11 (Fig. 16b) with a distinct increased chance of stress occurring towards maturity. For the 15/11 planting date (Fig. 16c) the number of predicted stress days is 6,83 yr^{-1}, while the greatest chance of stress occurrence is between pollination and maturity.

In summary therefore, Figs. 16a, b & c indicate that stress probability increases from about the 20th February onwards and hence, for hybrids requiring approximately 145 days of growth to come to maturity, planting early in October is advisable. It may be inferred from the changing stress vs time pattern with planting date that, should planting be delayed until after 15/11, the high

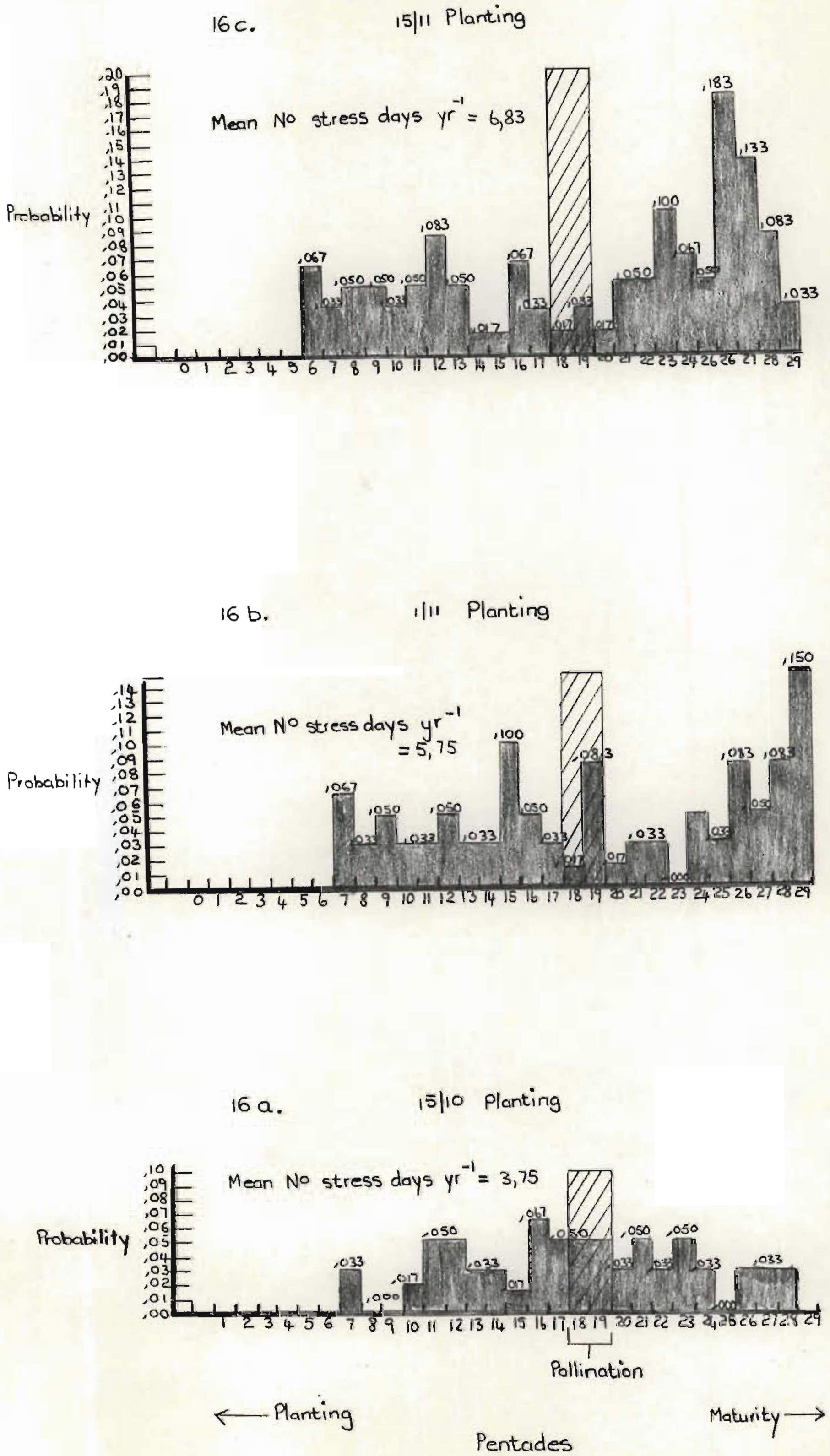


Fig. 16a, b & c. Stress pentade probability histograms for three planting dates at Cedara.

stress probability periods occurring during the later growth stages in the plant's life cycle could coincide with pollination with serious consequences.

ESTCOURT AND NEWCASTLE

Class A pan evaporation records were available for limited periods for both Estcourt and Newcastle and as these centres represent important farming areas in Natal, it was decided to apply an analysis to these data similar to that used for Cedara.

Rainfall and temperature means for Estcourt (20 yrs) and Newcastle (40 yrs) are listed in Tables 6 and 7. A cursory examination of these data indicate that these stations might have harsher and more exacting climates for maize production than Cedara. It was decided that because of the limited amount of data available, the low September and October rainfall and few rain days during these months, only the 1/11 planting date for Estcourt and Newcastle could be considered.

From the predictions made by the model, yield frequency distribution histograms were constructed for Estcourt and Newcastle and are presented in Fig. 17.

The predicted mean yields for Estcourt and Newcastle at 4,7 and 5,4 Mg ha^{-1} respectively, are considerably lower than the 7,9 Mg ha^{-1} expected at Cedara. The probability of obtaining yields between 8 and 10 Mg ha^{-1} at Estcourt is 0,25 and at Newcastle 0,37. At both centres drought risk is evident with the probability of obtaining yields below 2 Mg ha^{-1} at Estcourt being 0,25 and at Newcastle 0,37.

Estcourt (29°01'S 29°52'E Alt 1181 m)

	MONTH												TOTAL
	J	A	S	O	N	D	J	F	M	A	M	J	
Rainfall (mm)	10,7	19,0	33,0	68,9	99,5	128,6	105,1	113,9	106,9	52,9	21,8	6,0	766,3
Rain days	2	3	6	11	14	16	14	13	12	7	4	1	103
Max temp °C	18,7	21,4	24,1	25,4	26,1	27,1	27,3	26,9	25,6	24,0	21,2	18,9	
Min temp °C	2,4	5,1	8,1	11,3	12,8	14,3	15,0	14,9	13,7	10,4	6,0	2,6	
Mean temp °C	10,4	13,3	16,1	18,3	19,5	20,7	21,1	20,9	19,7	17,2	13,6	10,7	

TABLE 6 Mean monthly rainfall and mean number of rain days, mean temperature and mean daily maximum and minimum temperature for given months for Estcourt.

Newcastle (27°45'S 29°56'E Alt 1199 m)

	MONTH												TOTAL
	J	A	S	O	N	D	J	F	M	A	M	J	
Rainfall (mm)	17,2	13,9	36,8	78,1	130,0	135,8	159,3	141,3	126,3	46,1	24,9	9,8	919,5
Rain days	2	2	5	11	13	14	13	11	11	6	3	1	92
Max temp °C	20,1	23,1	25,7	27,1	27,7	28,9	28,4	27,7	26,4	25,1	22,5	20,1	
Min temp °C	1,6	4,9	8,4	11,9	13,1	14,3	15,0	14,9	13,2	9,5	4,7	1,4	
Mean temp °C	10,9	14,0	17,1	19,5	20,4	21,6	21,7	21,3	19,8	17,3	13,6	10,7	

TABLE 7 Mean monthly rainfall and mean number of rain days, mean temperature and mean daily maximum and minimum temperature for given months for Newcastle.

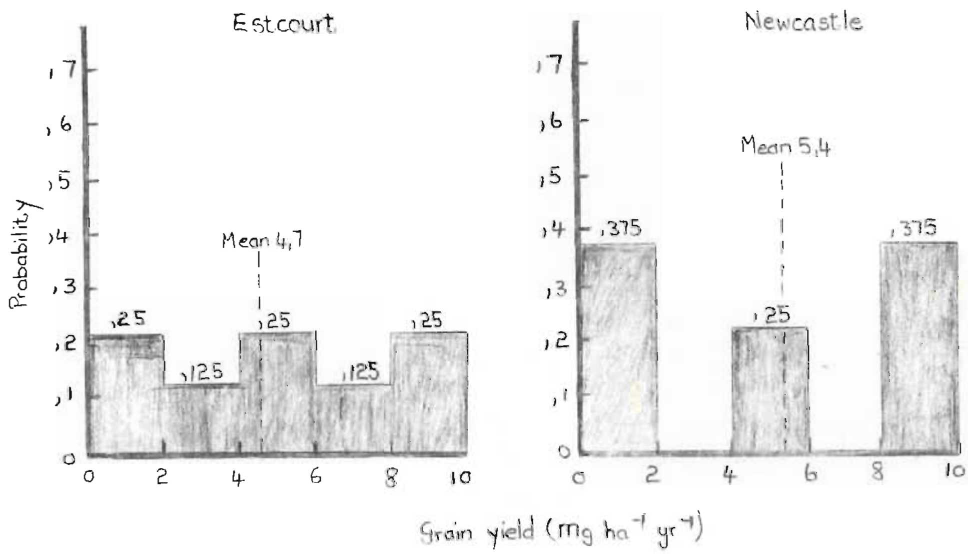


Fig. 17 Histograms of probability of occurrence of seasonal maize yields between selected limits at Estcourt and Newcastle.

STATIONS OUTSIDE NATAL

Climatic records were available for a limited number of stations spread throughout the recognised maize growing areas of South Africa, but outside Natal. It was decided to apply the existing Cedara : Doveton model to these data to compare approximately the maize production possibilities of these different areas. The widespread distribution of these additional stations will be observed from the map depicted in Fig. 18.

A comparison of rainfall and Class A pan evaporation between the Natal locations already considered and the stations outside Natal is presented in Table 8.

Location	Annual Rainfall (mm)	Av. No. Rain Days yr^{-1}	Mean Daily 'Growing Season' E_O (mm)
Cedara	880,0	149	5,0
Estcourt	766,3	103	6,0
Newcastle	919,5	92	5,6
Bethlehem	677,4	104	7,2
Hoopstad	442,8	44	8,9
Potchefstroom	612,0	57	7,5
Krugersdorp	785,8	96	5,2
Ermelo	755,6	91	5,3
Standerton	719,3	71	6,1

TABLE 8 Mean annual rainfall and number of rain days; and mean daily class A pan evaporation for the growing season for nine maize growing locations.

From the predictions made by the model, yield frequency distribution histograms were constructed for Bethlehem, Hoopstad, Potchefstroom, Krugersdorp, Ermelo and Standerton and are presented in Fig. 19.

Of these stations Ermelo and Krugersdorp appear to have the most suitable climates for maize production. Both display little chance of crop failure and mean yields of 5,4 and 5,3

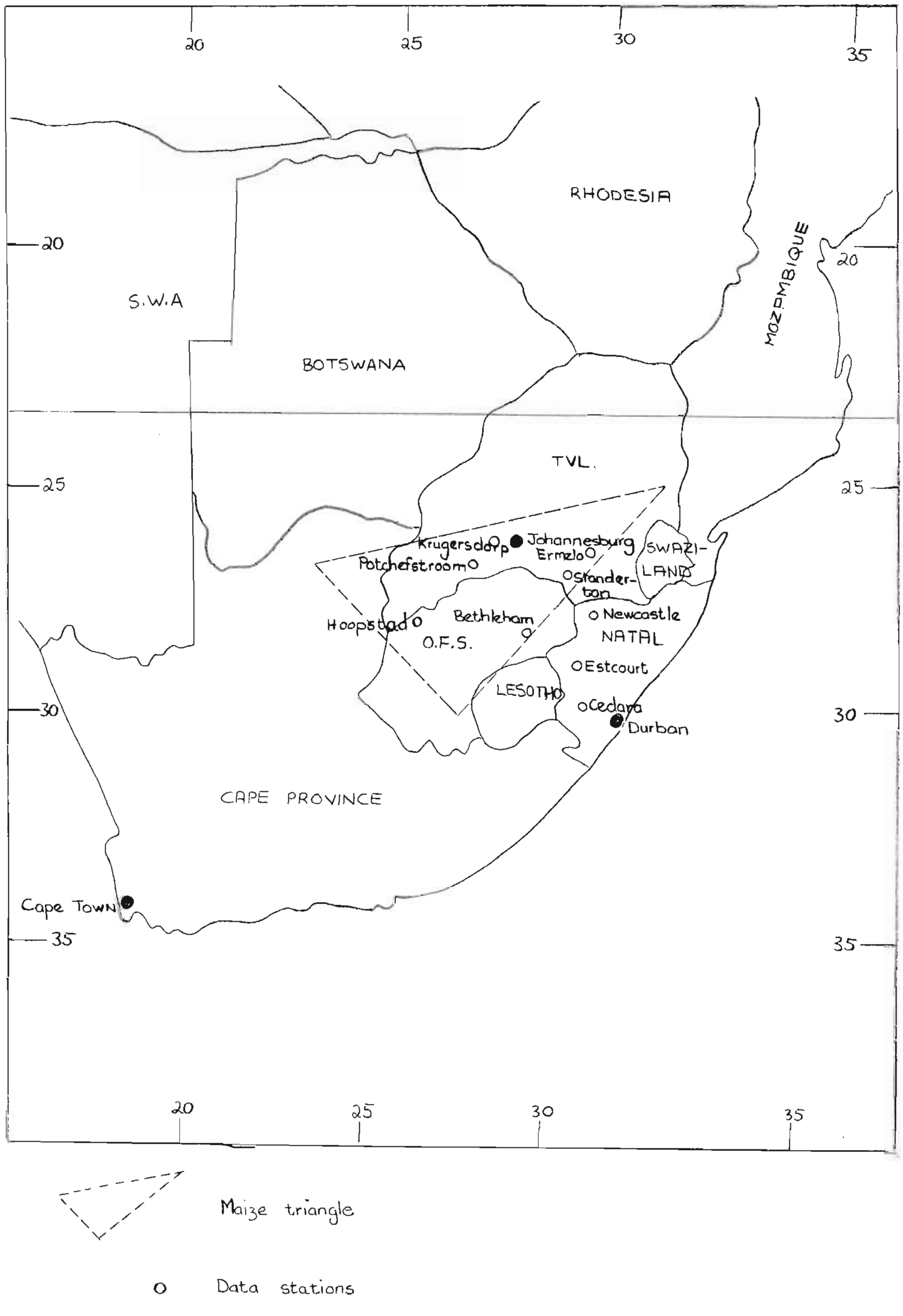


Fig. 18 Map of Republic of South Africa showing location of data stations.

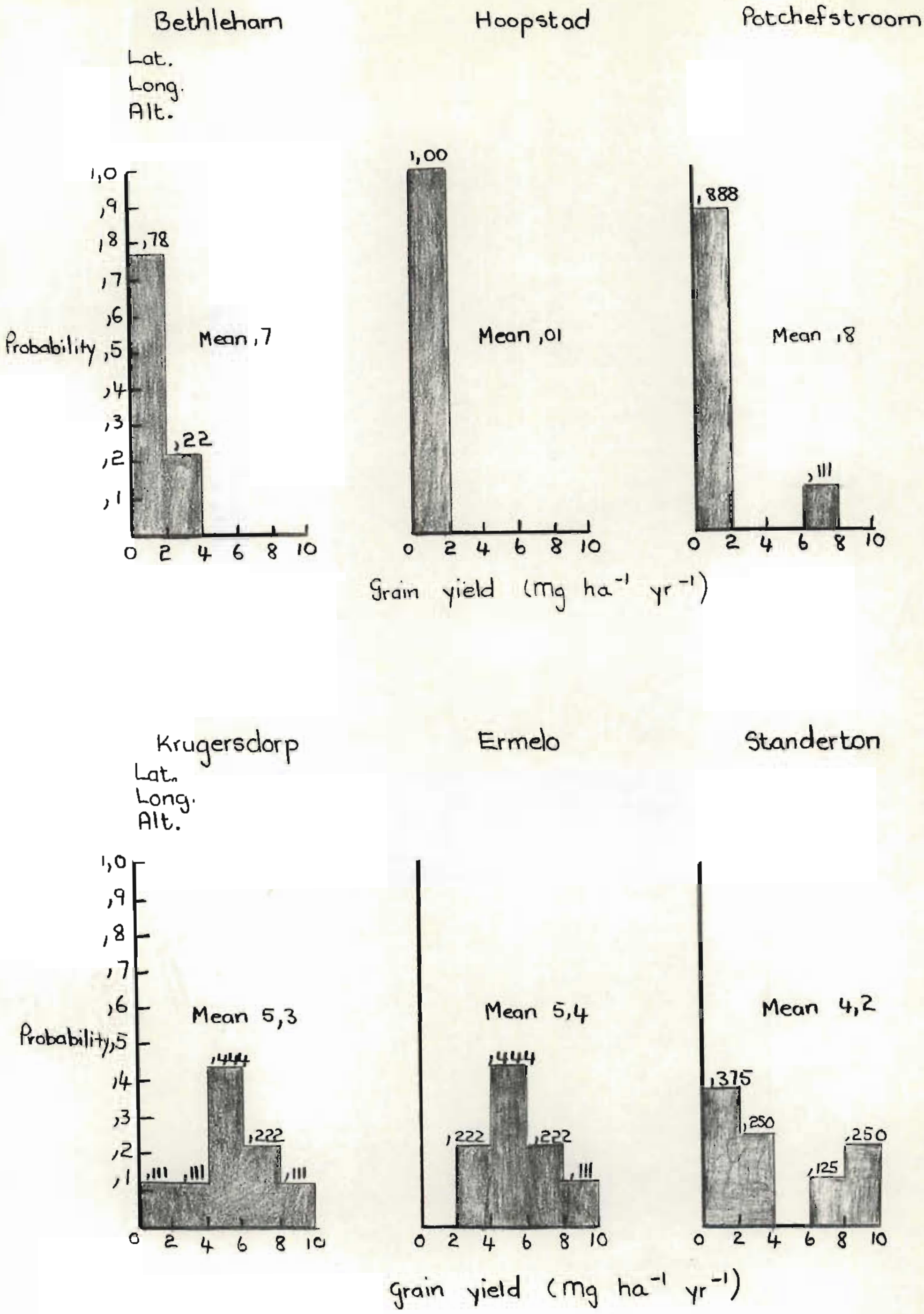


Fig. 19 Histograms of probability of occurrence of seasonal maize yields between selected limits at Bethlehem, Hoopstad, Potchefstroom, Krugersdorp, Ermelo and Standerton.

Mg ha^{-1} respectively, may be expected. The Standerton climate is less reliable since a chance of 1 in 3 exists of obtaining yields less than 2 Mg ha^{-1}. The model predicts high drought risks for Bethlehem, Hoopstad and Potchefstroom.

DISCUSSION

Except in the case of Cedara where three planting dates were considered, analyses for all other locations were made using planting date 1/11. In the ensuing discussion therefore, whenever comparisons between stations are made the Cedara 1/11 planting only, is considered. The model assumes similar soil characteristics and plant growth patterns at all locations. Although the model should be modified by substituting soil characteristics, length of growing season, soil depth, plant population density and root growth pattern, as applicable to new areas considered, it was executed as used at Cedara. The results therefore indicate how a maize crop managed as at Cedara would perform in the chosen regions and provides valuable information regarding the relative suitability of areas for maize production.

It is not difficult to modify the computer programme to take into account these edaphic and technological factors.

Natal

Results from the Cedara, Estcourt and Newcastle analyses may be used to compare the effectiveness of their different climates for the production of maize and the results are summarized in Table 9.

Although Newcastle experiences the highest annual rainfall, it also presents a relatively high drought risk for maize production

Location	Av. Annual Rainfall (mm)	Av. No Rain Days yr^{-1}	Av. No Stress Days	Mean Yield Decrement $Mg\ ha^{-1}$	Mean Yield $Mg\ ha^{-1}$	No. Years Considered
Cedara	880,0	149	5,75	2,1	7,9	12
Estcourt	766,3	103	17,4	5,3	4,7	8
Newcastle	919,5	92	13,0	4,6	5,4	8
Ermelo	755,6	91	12,3	4,6	5,4	9
Krugers-dorp	785,8	96	13,4	4,7	5,3	9
Stander-ton	719,3	71	15,1	5,8	4,2	9
Potchef-stroom	612,0	57	30	9,2	0,8	9
Bethlehem	677,4	104	30	9,3	0,7	9
Hoopstad	442,8	44	30	9,9	0,01	5

TABLE 9 Rainfall and number of predicted stress days and their effect upon yield at three locations in Natal and six locations outside Natal.

and its predicted average yield is only 0,7 Mg ha^{-1} higher than Estcourt which receives 150 mm less rain annually. Predicted mean annual production for both Estcourt and Newcastle is approximately 3,0 Mg ha^{-1} less than Cedara (7,9 Mg ha^{-1}).

From the predictions made in Natal, it can be seen that Cedara has a reliable seasonal weather pattern for maize production. At both Estcourt and Newcastle the potential for high yields exist, but drought risk is great.

Additional analysis showed that early planting at Cedara improves the chance of consistently obtaining high yields.

Yield predictions for other areas

Of the stations outside Natal, predictions for both Ermelo and Krugersdorp showed these areas to be better suited for maize production than Estcourt. Their mean annual expected yields were almost identical to that obtained for Newcastle (5,4 Mg ha^{-1}) whilst both displayed less seasonal yield variation than the Natal station. It appears that Standerton (4,2 Mg ha^{-1}) and Estcourt (4,7 Mg ha^{-1}) possess a similar potential for maize production.

The model predicts poor maize production potential for Bethlehem, Hoopstad and Potchefstroom (0,7, 0,01 and 0,8 Mg ha^{-1} respectively). At these sites successful maize cultivation would depend upon the selection of soils with favourable water holding characteristics, water conservation measures, the use of low plant populations and wide row spacing. These drought evasive tactics are in fact adopted by farmers in these areas, thereby ensuring more regular and somewhat higher yields than predicted (approx. 0,5 Mg ha^{-1}) by the Cedara : Doveton model. South Africa's low average maize yield of approximately 1,0 Mg ha^{-1} is largely attributable to the regular ploughing of vast areas with similarly low potential.

The model here described, permits yield predictions to be made for various sites considering stage of plant development and using daily values of available soil moisture and atmospheric evaporative demand. It permits a precise evaluation of climatic potential with special reference to moisture supply and can make possible accurate comparisons between locations.

CHAPTER 5

IRRIGATION PLANNING

The yield probability model discloses the mean number of stress days that may be expected per season at any particular location. This information has a valuable use as it indicates the amount of supplementary irrigation that is required in an area, and together with the estimated yield decrement per stress day, it could also provide an estimate of the possible benefit which might be derived from irrigation. Furthermore, the model may be used to compare the potential for irrigation of different localities, and the determination of the level above which (datum level) available soil moisture (ASM) should be maintained to produce a selected yield.

ASSESSMENT OF WATER USE EFFICIENCY

To enable the entrepreneur to make decisions he must be able to evaluate the efficacy of supplementary irrigation. This can best be accomplished by determining the number of stress days eliminated per unit of supplementary irrigation. The factor used to describe this function will be named the Stress Day Reduction Factor (F) and is defined as the number of stress days eliminated per unit increase in maintained datum ASM (DASM). DASM is defined as that value of available soil moisture below which soil moisture is not allowed to fall.

Hence, by definition

$$F = \frac{d}{dASM} (NE) \qquad \text{..........} \ (5)$$

where NE = number of stress days eliminated.

Available soil moisture can be derived from rainfall or irrigation, but when investigating irrigation possibilities it must be assumed that the source is supplementary irrigation alone.

APPLICATION OF MODEL TO IRRIGATION PLANNING

Consider the three locations in Natal (Cedara, Estcourt and Newcastle) for which yield predictions have been made. To date most irrigation decisions have been based upon soil moisture status. It was therefore decided to find out from the computer print-out at which values of CASM, stress is most likely to occur. Hence, histograms of the probability of occurrence of different values of CASM were constructed and are illustrated in Fig. 20. These figures reflect that there is an almost equal chance of stress occurring at any given value of ASM ranging between 40 and 80%. This is particularly true in the case of Newcastle.

The practical significance of this fact to irrigation planning is the implication that increasing the minimum DASM from 50 to 60% say, eliminates approximately the same number of stress days as would be the case if DASM were increased from 60 to 70%. Selection of DASM level is a management decision and does not alter the amount of water used.

The management decisions to increase DASM from 50 to 60% and

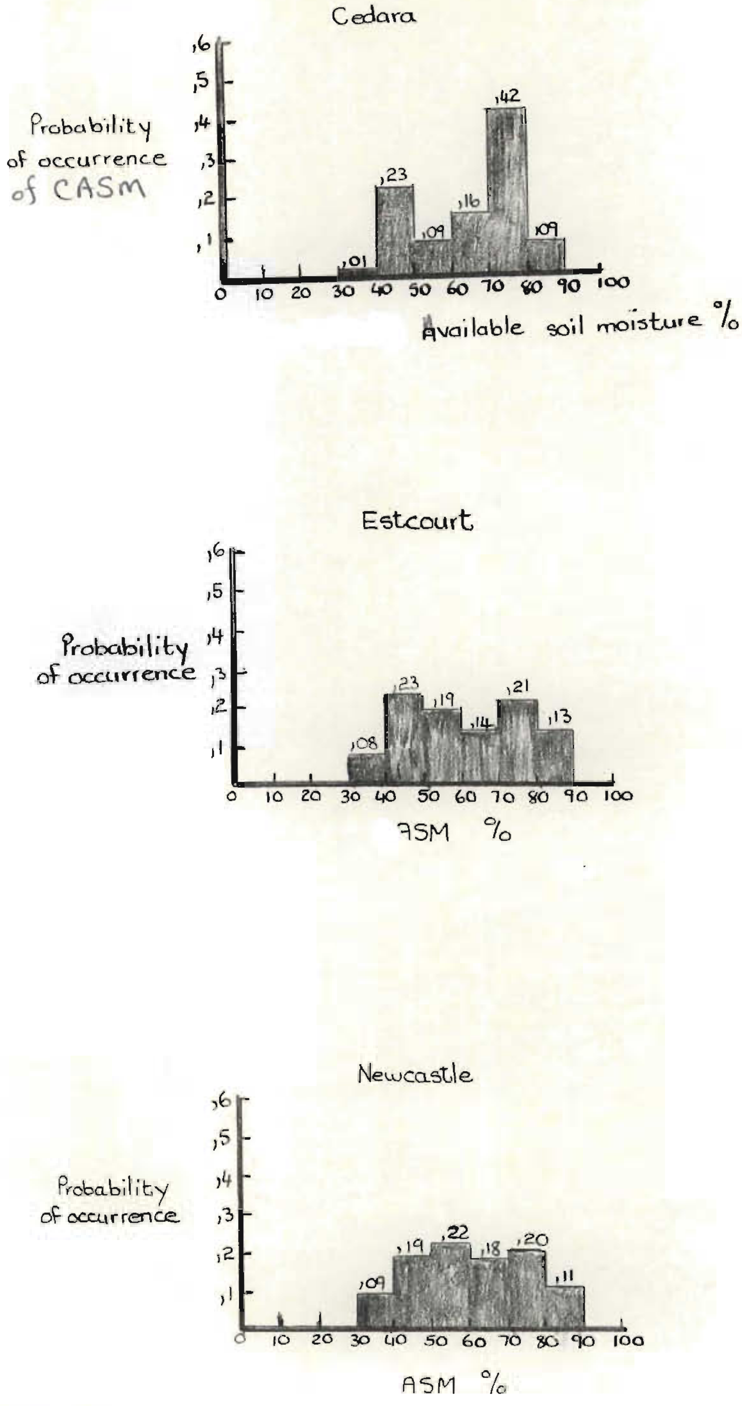


Fig. 20 Histograms of the probability of occurrence of given values of critical available soil moisture at Cedara, Estcourt and Newcastle.

to increase DASM from 60 to 70% will result in the same decrease in number of stress days per unit of increased DASM, i.e. the Stress Day Reduction Factor (F) is constant irrespective of the chosen level of DASM.

In conclusion therefore it appears that water use efficiency is independent of the DASM selected, but might vary with climate.

VARIATION OF MANAGEMENT ACCORDING TO CLIMATE

In many instances when planning irrigation, the main difficulty is deciding on the datum level of ASM.

Although the previous section indicates that F is independent of ASM, it is also intimated that F might vary with climate. This relationship will now be investigated.

F may be determined by plotting the number of stress days eliminated (NE) against the value of ASM which must be maintained to ensure the non-occurrence of this number of stress days. Such a graph is given in Fig. 21, and F may be found from the slope of this curve.

It is evident from Fig. 21 that the slopes of the curves obtained for different places vary markedly. Hence it may be deduced that F and the efficiency of use of supplementary water depends upon climate. In the present investigation values of F determined from Fig. 21 are 0,33, 0,24 and 0,11 days for Estcourt, Newcastle and Cedara respectively.

It can be seen that if an irrigation programme assures that the DASM level is 50% say, then different numbers of stress days will be eliminated at each centre. It thus appears that DASM

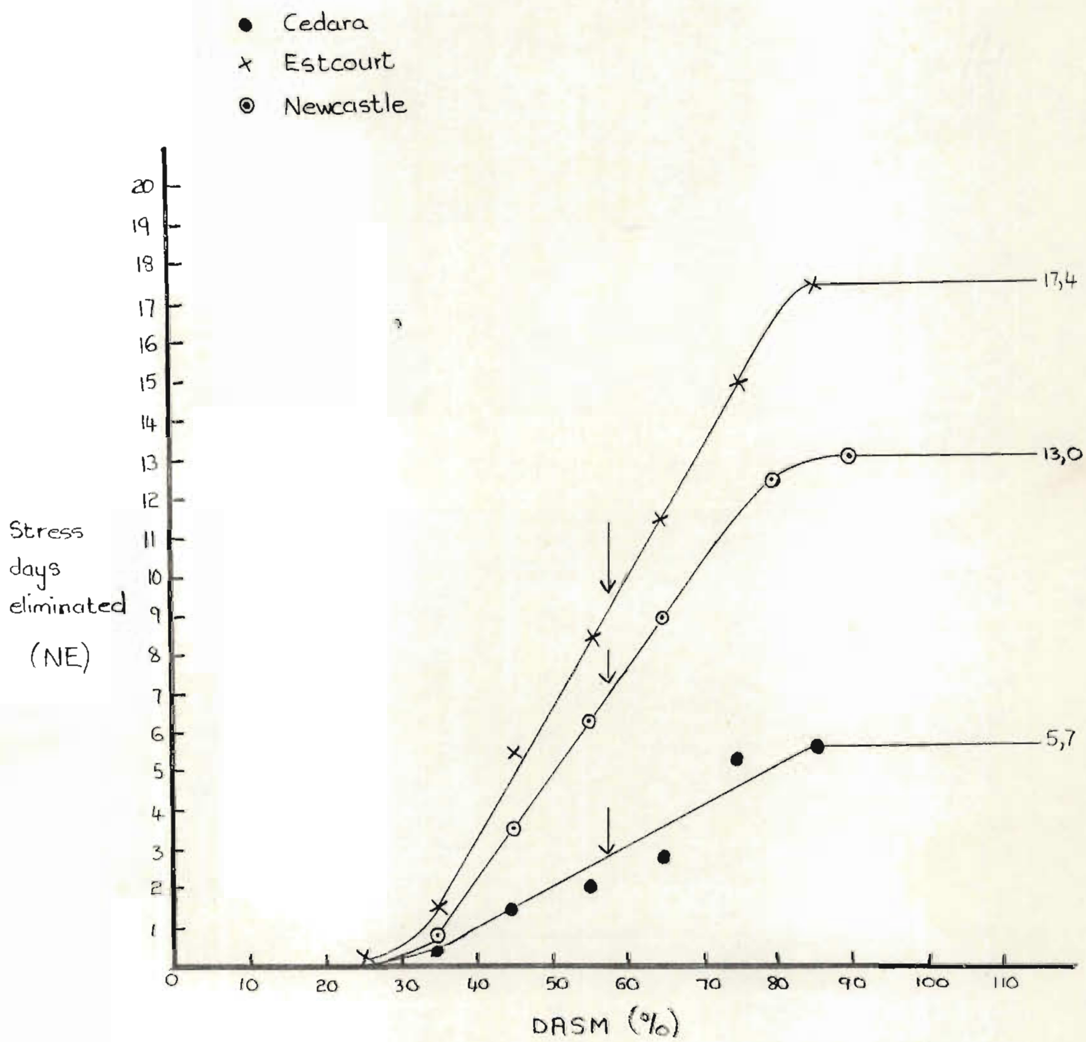


Fig. 21 Available soil moisture levels to be maintained if a selected number of stress days are to be eliminated.

must be chosen according to climate and will vary from place to place.

Maximising irrigation efficiency

In an effort to assist management decision making a theory for maximising irrigation effectivity will now be developed.

The symbols to be used are as follows:-

Symbol	Interpretation	Unit
L	Decrease in yield per stress day	%
C	Additional capital required for supplementary irrigation	R
ASM	Available soil moisture	%
DASM	Datum available soil moisture	%
TSM	Total available soil moisture	mm
A	Total area irrigable	ha
p	Period between irrigations	day
NE	No of stress days eliminated	
a	Area covered per irrigation unit	~~R a~~ ha day^{-1}
c	Cost per irrigation unit	R
E	Mean daily evapotranspiration	mm day^{-1}
H	Irrigation application rate	mm day^{-1}
S	Total water storage	l
R	Profit* per unit area	R ha^{-1}
YPot	Potential yield	Mg ha^{-1}
Y	Yield per unit area	Mg ha^{-1}
I	Income per unit mass of produce	R kg^{-1}
G	Length of growing season	day
F	Stress reduction factor	day
f	Fixed farming costs per unit area	R ha^{-1}
n	Life of scheme	yr

*The subscripts "i" and "o" when applied to symbols shall indicate that the appropriate value of the variable with or without irrigation respectively is to be used.

The treatment shall ignore rainfall and it shall be assumed that additional labour costs for moving irrigation equipment are negligible and that it is possible to apply in one day as much water as is required to restore ASM to field capacity.

The object of the exercise shall be to set up rules whereby the difference between profits with and without irrigation may be maximised. Let this difference in profits be denoted X.

The extent of an irrigation scheme may be limited by:-

1 Capital outlay,

2 Total water available for irrigation, or

3 Application rate.

Hence to promote decision making for a particular scheme, tests to ascertain which factor will limit the project must be defined.

Limitation 2. If water is not to limit the area to be irrigated than

$$A \leq 10^3 \frac{S}{GE} \text{ (ha)} \qquad \ldots\ldots\ldots\ldots (6)$$

Limitations 1 & 3. There is an interaction between limitations 1 & 3 as application rate is a function of finances. Hence, the argument proceeds as follows:-

The number of irrigation units purchased $= \frac{C}{c}$

and the area covered per day per irrigation unit $= a \frac{C}{c}$ $\qquad \ldots\ldots\ldots\ldots (7)$

Now, since

$$F = \frac{d}{dASM}(NE)$$

and the straight line curves in Fig. 21

converge at an ASM of 30%

$$ASM = \frac{NE}{F} + 30$$

$$\text{Hence, } p = \frac{(100 - DASM)\ TSM}{100.E} \quad (day)$$

$$\text{or, } p = (70 - \frac{NE}{F})\frac{TSM}{100.E} \ (day) \quad \ldots\ldots\ldots (8)$$

Assuming adequate water ([100-DASM] TSM/100) to bring rooting depth to field capacity, may be applied in one day; if the area irrigable

$$A = p\ (a\frac{C}{c})$$

then from eqn 8

$$A = (70 - \frac{NE}{F})\frac{TSM}{100.E}\ a\frac{C}{c}\ (ha) \quad \ldots\ldots\ldots (9)$$

The value of A found from eqn 9 may not be greater than that found in eqn 6. Furthermore (condition 3)

$$A \leq \frac{H}{E}\ (a\frac{C}{c}) \quad \ldots\ldots\ldots (10)$$

The largest area A permitted by the scheme may be calculated from eqns 6, 9 and 10.

The difference between profits obtained with and without irrigation are given by,

$$\triangle R = (R_i - R_o) \quad \ldots\ldots\ldots (11)$$

$$\text{Now} \quad Ri = AY_iI - fA - C/n$$

$$\text{and} \quad Ro = AYoI - fA$$

$$\therefore \triangle R = AI(Yi - Yo) - C/n \quad \ldots\ldots\ldots (12)$$

$$A = (70 - \frac{NE}{F})\frac{TSM}{100.E}\ a\frac{C}{c}$$

Now,

$$Yi = Yo + \frac{NE(L)YPot}{100} \qquad \text{.........} \ (13)$$

$$\therefore \ Yi - Yo = \frac{NE(L)YPot}{100}$$

From eqn 12

$$\triangle R = AI \ (Yi - Yo) - C/n$$

$$= \left(\frac{A.I.NE.L.YPot}{100}\right) - C/n$$

Now substituting for A from eqn 9

$$\triangle R = \left\{\left[\left(70 - \frac{NE}{F}\right) \frac{TSM}{100.E} \quad a\frac{C}{c}\right] \frac{I.NE.L.Pot}{100}\right\} - C/n$$

$$= \left(70NE - \frac{NE^2}{F}\right) \frac{TSM}{10000.E} \ a\frac{C}{c} \quad I.L.Y.Pot - C/n$$

Put $\frac{TSM}{10000.E} \quad a\frac{C}{c} \quad I.L.Y.Pot = J$

$$\therefore \quad \triangle R = -\frac{J}{F} NE^2 + 70J.NE - C/n \qquad \text{.........} (14)$$

$$\frac{d}{dNE} \ (\triangle R) = -2\frac{J}{F}NE + 70J$$

$\therefore$ Maximum when

$$NE = 35F \qquad \text{........} \ (15)$$

or, $NE = \frac{1}{2}(100\text{-ASM at which } NE = 0) \ F$

Substituting the F value for Estcourt, Newcastle and Cedara as obtained from Fig. 21 in eqn 15 it is found that for

Estcourt NE = 11,55 days, for

Newcastle NE = 8,40 days and for

Cedara NE = 3,85 days.

These NE values will be attained by adopting a datum ASM level of approximately 65%. Although it was expected that different DASM levels might be required for different locations this is not found to be the case.

DISCUSSION

The practical application of these findings should have important economic repercussions as irrigation scheduling is often based upon the arbitrary selection of the DASM level.

A theory (eqn 15) for maximising irrigation effectivity has been developed and should simplify irrigation planning, scheduling and design. The important factor required by the theory is the stress day reduction factor F, which defines the number of stress days eliminated per unit increase in DASM level for a given site. Provided F can be ascertained, the entrepreneur has a precise analytical method for determining the most efficient DASM level for his particular conditions.

It can also be seen that a system like drip-irrigation, which ensures consistently high ASM levels, thereby eliminating all stress days, must outperform spray irrigation where the perpetual maintenance of high DASM levels is a practical impossibility if the normal cyclical system involving the rotation of piping networks is employed.

CHAPTER 6

EFFECT OF SOIL TYPE ON SHAPE OF STRESS DAY DISCRIMINATION CURVE

In Chapter 2 the development of a stress day discriminating curve for a Doveton clay loam soil is described. In order to demonstrate the model's usefulness for comparing the climatic potential for maize production in different locations, the Doveton curve has been used throughout this thesis. Where other soil types occur, however, the appropriate discriminating functions should be used to ensure reliable predictions are obtained.

Differences in shape between the discriminating functions for different soils will reflect the differences in ease of water extraction by plants from these soils. A soil with a higher clay content than a Doveton will produce a flatter curve, while one with a higher sand content may be expected to have a steeper curve. Examples are illustrated in Fig. 22.

On a day when an E_O reading of 5 mm is recorded for example, maize on a clay would wilt at ASM values 55%, while plants on the sand would be able to tolerate ASM values as low as 20% before wilting.

Determination of discriminating function

Before widespread application of the yield prediction model is possible, discriminating functions for the more important maize producing soils are required. The use of mass measuring lysimeters for establishing these functions is an exacting, time consuming, laborious and expensive operation. An alternate

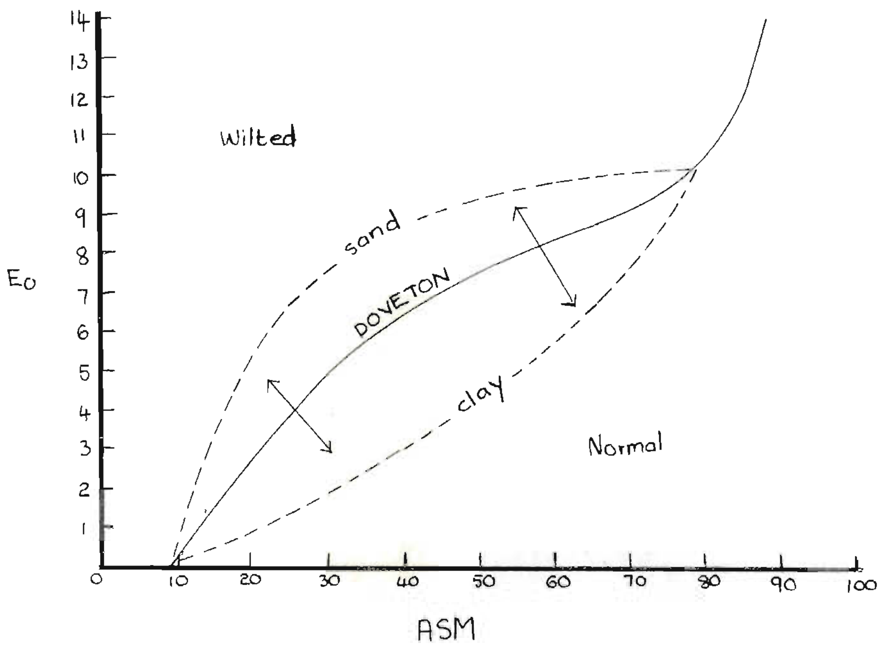


Fig. 22 An example of variations in the discriminating curve that may be expected as the soil's clay content varies.

method of obtaining discriminating functions for individual soils by modifying the Doveton curve, using soil moisture suction data, will now be described.

Method

Modification of the Doveton curve to produce a discrimination curve applicable to given soils was carried out in the following steps:-

1. Using the Doveton soil moisture suction curve illustrated in Fig. 23, Table 10 was constructed. Values for soil moisture suction corresponding to chosen ASM values were listed in columns 1 and 2. E_O values corresponding to the selected ASM values were extracted from the original Doveton discriminating curve (See Fig. 9) and are listed in column 3 of Table 10.

Suction (bars)	ASM (%)	E_O (mm)
0,3	100,0	-
0,4	97,0	-
0,5	93,0	-
0,6	89,0	-
0,7	85,0	15,0
0,8	82,0	12,5
0,9	78,0	10,7
1,0	75,0	10,0
2,0	42,0	6,5
3,0	33,0	5,1
4,0	28,0	4,2
5,0	25,0	3,3
6,0	22,0	2,8
7,0	19,5	2,1
8,0	17,0	1,8
9,0	14,5	1,2
10,0	12,0	0,6
11,0	9,5	-
12,0	7,4	-
13,0	4,0	-
14,0	2,0	-
15,0	0,0	-

TABLE 10 Soil moisture suction values (Column 1) corresponding to chosen ASM levels (column 2) as appearing in the Doveton soil moisture suction curve, Fig. 23. E_O values (column 3) corresponding to ASM values in the Doveton discriminating curve, Fig. 9.

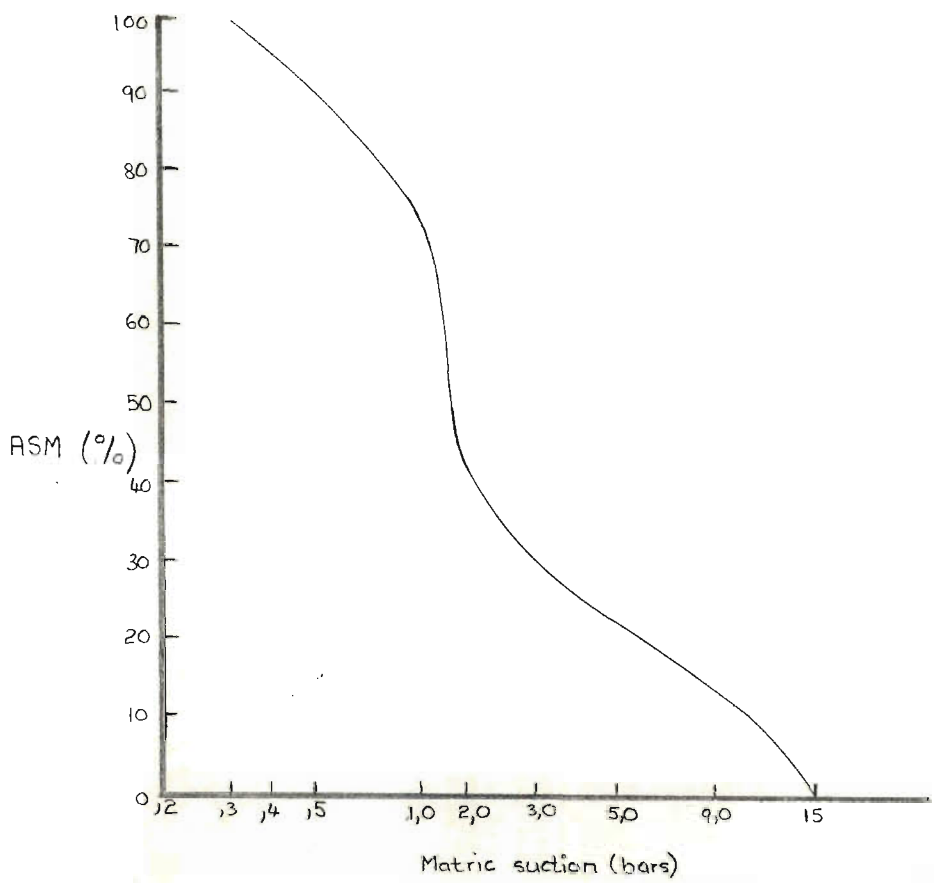


Fig. 23 Doveton soil moisture suction curve.

2. Next, the curve illustrated in Fig. 24 was constructed by plotting from Table 10 the corresponding values of soil moisture suction (column 1) versus E_O (column 3), Fig. 24 is a discriminating curve of evaporative demand and soil moisture suction which is applicable to any soil type.
3. Since the computer programme uses a discrimination function based on available soil moisture, rather than soil moisture

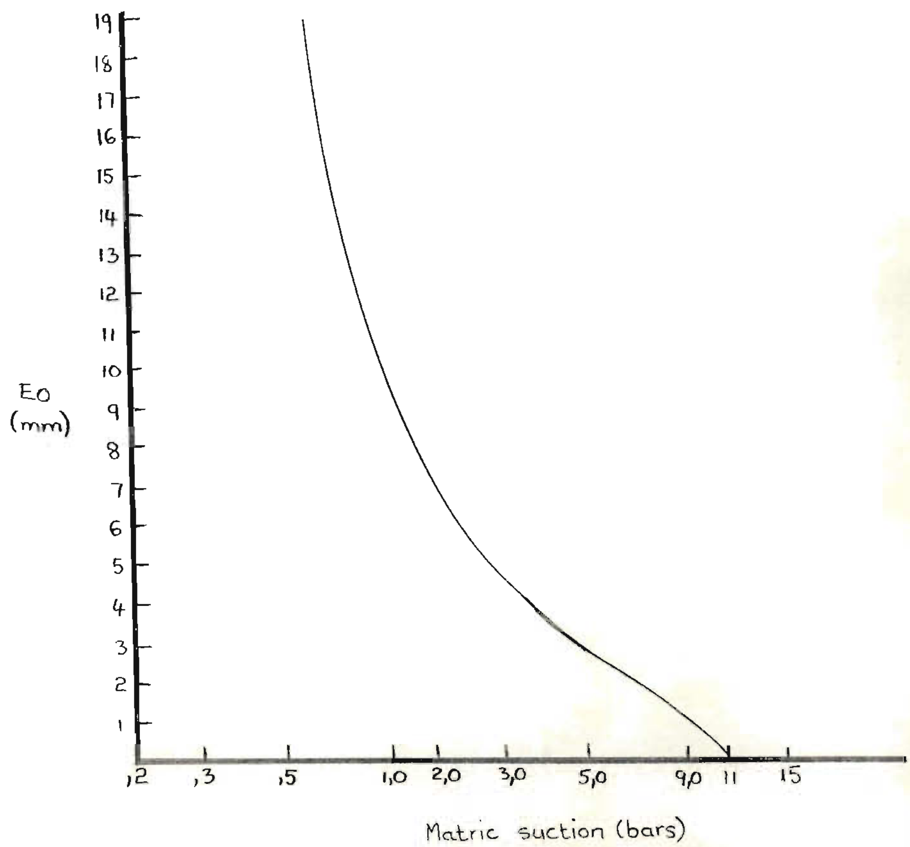


Fig. 24 Doveton matric suction vs evaporative demand curve.

suction, it is convenient to transform suction values to ASM. This can be carried out simply by substituting appropriate values of ASM for the soil suction values in Fig. 23.

Making use of soil moisture suction values determined by Scotney (1970) for a number of Natal soils, discrimination functions for a selection of these soils were constructed and are illustrated in Fig. 25.

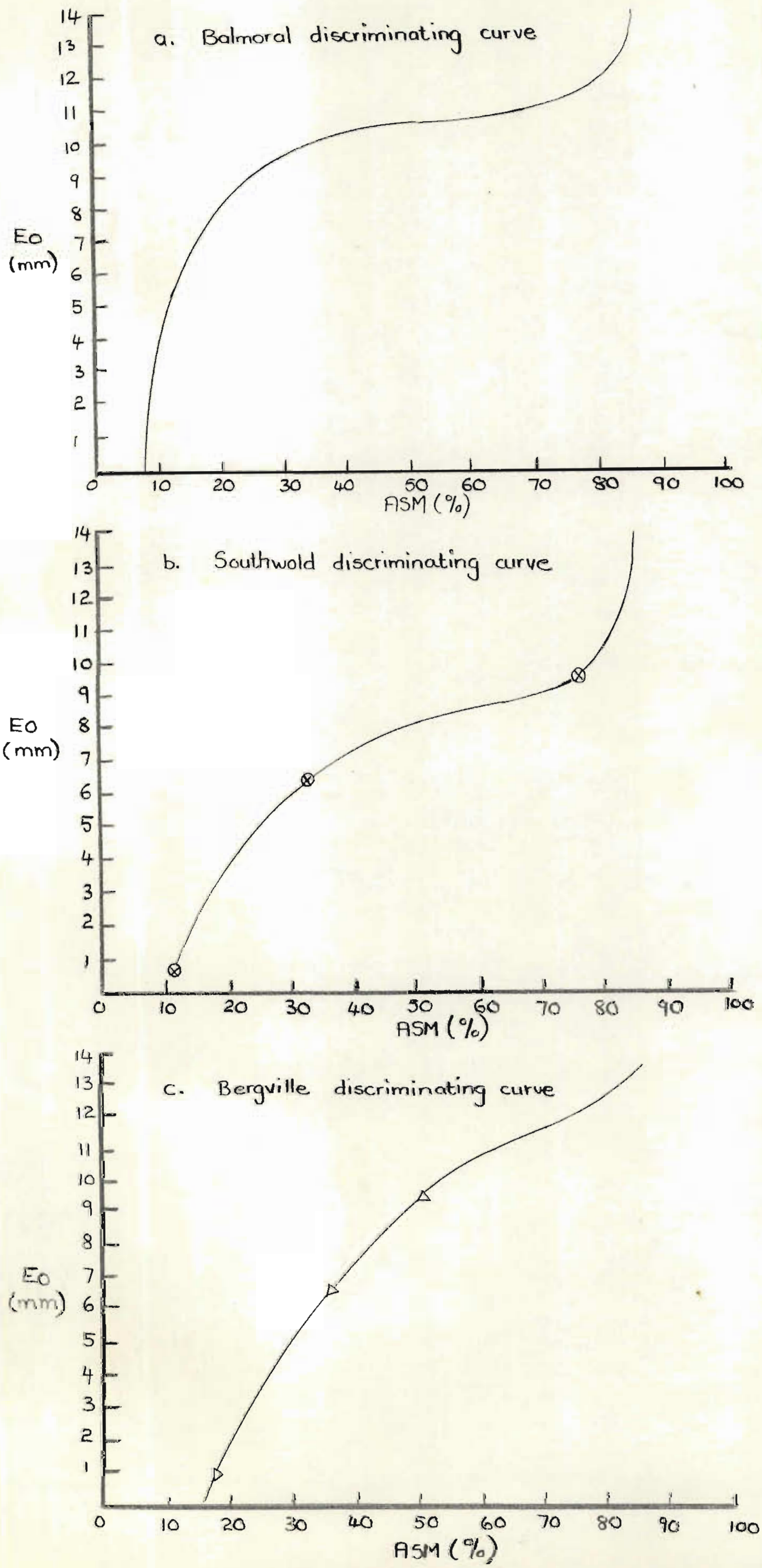


Fig. 25 a, b & c. Discriminating curves derived for three Natal soils

DISCUSSION

The practical application of the yield probability prediction model is greatly extended if discrimination curves for different soils are available. A method for producing such curves has been explained making it now possible to apply the model to virtually any maize producing area. The significance and importance of this modification is self-evident.

Discriminating functions are extremely sensitive to soil type, as is evident from the marked differences between the shapes of the curves illustrated in Fig. 25. A crop growing on a Balmoral for example will tolerate higher atmospheric evaporative demands before wilting than a crop on a Bergville. Weather conditions being identical and water holding capacities similar, less stress days will be recorded on the Balmoral with resultant higher yields.

GENERAL DISCUSSION

In its existing form the Cedara : Doveton model makes possible maize grain yield predictions for the hybrid SA 60 grown on a Doveton soil at Cedara. Without modification, the model can be used to compare the relative suitability of different climates for maize production at population densities similar to those used in the developmental experiments.

If accurate yield predictions are required for other locations, however, the computer programme will need to be altered in accordance with the requirements of the new site. Information about a location which must be available before yield predictions are possible, is the following:-

<u>Soil type</u>

i The soil's moisture suction curve must be available in order to construct the appropriate discriminating curve.

ii The soil's moisture holding characteristics at different depths must be known to determine the soil's water holding capacity within the crop's root zone. These characteristics vary with profile depth.

iii It must be known whether an impervious or semi-impervious layer exists within, or just below the normal root zone, as account will have to be taken of this when determining the soil's water storage capacity. Such layers are characteristic of the important Leksand, Sandy Avalon and to a lesser extent Avalon soils in Natal, and contribute significantly towards their high yield potential.

Plant

i The length of growing season of the crop must be known as this influences the amount of moisture required from planting to maturity.

ii In order to compute soil moisture removal patterns, knowledge must be available of root distribution and profileration, as these vary with time throughout the soil profile.

iii Wide crop rows and low plant populations, as used in many of the more arid parts of South Africa, reduce the crop's potential yield but have the effect of making soil moisture reserves last longer. Allowance will have to be made for these facts in the computer programme when these planting patterns are used.

Evaporation

The model uses daily Class A pan evaporation data for yield predictions. Unfortunately these records are not plentiful, so that in many cases an estimate of evaporation from other climatic records will have to be used. It is not anticipated that the use of these estimates will reduce appreciably, the accuracy of the model's predictions.

Rainfall

The acquisition of the daily rainfall records required by the model should provide no problem.

Should widespread use of the yield prediction model be planned, provision will have to be made in the computer programme for the storage of a wide range of discriminating curves, lengths of growing season, rooting pattern and soil depth permutations and soil moisture storage capacities. The computer programme can easily accommodate these modifications, and the appropriate features for a given locality would be used in the model when executing prediction computations.

Besides the model's use in agronomic planning, irrigation scheduling, economic and sociological studies, its application should prove of considerable value to agricultural research workers in their quest to improve crop technology. The model's ability to isolate and identify the confounding effect of weather, will greatly simplify the task of interpreting the results of field experiments that frequently display inexplicable, complex seasonal variations.

The type of problem tackled in this thesis was completely dependent upon the use of an electronic digital computer for its successful solving. This powerful tool will in future be increasingly relied upon by agricultural research workers for the solving of similar and more complex problems.

Provided the crop's basic behaviour patterns have been established and are thoroughly understood, mathematical models can be used to simulate numerous sets of environmental and soil conditions, thereby rapidly providing results that would otherwise only be achieved after many years of expensive and laborous field experiments.

Model limitations

In order to allow for the construction of a practical working yield prediction model, it was necessary to make assumptions that simplified some of the extremely complex plant/soil moisture relationships found in the field. Brief comment is made below of the two most important assumptions applied.

The first and most important simplification brought about, concerns the concept of wilting being a function of atmospheric evaporative demand and soil moisture suction. Evidence obtained in the mass measuring lysimeter experiment indicated that uniform moisture removal from the entire lysimeter soil profile could be assumed. Wilting could therefore be associated with a specific relationship between soil moisture suction and atmospheric evaporative demand. Successful application of the yield prediction model is dependent upon the extrapolation of these findings to field conditions. Under field conditions, however, the suction patterns existing at the soil/root interface resulting in wilting are unlikely to be identical throughout the entire rooting depth. In order to accommodate this situation the rooting depth was considered in a series of 300 mm layers and a stress day was only recorded when the soil moisture content of all layers was at or below CASM. If, for example the soil moisture content of only three out of four layers was at or below CASM, a stress day was not recorded, provided the remaining layer could meet the plant's moisture requirements. Although not a perfect solution to the problem presented by varying soil moisture content with rooting depth, the model was nevertheless able to satisfactorily accommodate the situation.

The second important simplification concerns the rate of drainage of gravitational water through the soil profile. The rate of drainage of gravitational water through an unimpeded profile is a continuous process and the use of a neutron probe on a Doveton soil at Cedara has indicated that gravitational water will evacuate a 900 mm profile in 3 days. Since the yield prediction model operates on a daily basis, a step process of gravitational water movement, at the rate of 300 mm per day was adopted. A similar technique was used by Shaw (1963) when estimating the soil moisture status under a growing maize crop.

A limit upon the amount of moisture that could pass through a 300 mm layer in one day had also to be decided upon since it would be unreasonable to accept that no limit exists. In the model the limit set for this amount was arbitrarily selected as being equivalent to the field capacity of the layer in question. It is not considered that this constraint had any marked effect upon the accuracy of the yield predictions made by the model, since it is highly improbable that a stress day would have occurred within the four to five days necessary for the removal from the rooting zone of such copious supplies of gravitational water.

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APPENDIX

COMPUTER PROGRAMME LISTING

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
*IOCS(CARD,1132 PRINTER,DISK,TYPEWRITER)
      DEFINE FILE 1(145,2,U,NWW)
      DEFINE FILE 2(1,8,U,NAS)
      DEFINE FILE 3(145,2,U,NET)
      DEFINE FILE 4(1,8,U,NFC)
      DEFINE FILE 5(145,8,U,NEX)
      DEFINE FILE 6(145,2,U,NRL)
      DEFINE FILE 7(180,2,U,NCW)
      DEFINE FILE 8(200,2,U,NEV)
      DEFINE FILE 9(145,2,U,NRN)
      DEFINE FILE10(145,2,U,NTW)
      DEFINE FILE 11(157,2,U,NRR)
      DEFINE FILE 12(145,2,U,NAP)
      DEFINE FILE 13(10,260,U,NRO)
      DEFINE FILE14(145,2,U,NKF)
      DEFINE FILE15(145,2,U,NCC)
      DEFINE FILE 16(300,65,U,NRD)
      DEFINE FILE 17(300,65,U,NED)
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C     RAYN WRITES RAINFALL TO DISK
C     EVAP WRITES EVAPORATION TO DISK
C     FYLE WRITES   CASM TO DISK
C                   RUNOFF TO DISK
C                   ET/EO RATIO TO DISK
C                   ROOT PROGRESS TO DISK
C                   FASM TO DISK
C     PREP CALCULATES ETRAN(N) AND CASM(N) AND WRITES TO DISK
C     WIN CALCULATES API WRITES IT TO DISK
C                   RUNOFF WRITES IT TO DISK
C                   WATER WRITES IT TO DISK
C     AW1 COMPUTES WATER BUDGET DAY 1 TO 16
C     AW2 COMPUTES WATER BUDGET DAY 17 TO 28
C     AW3 COMPUTES WATER BUDGET DAY 29 TO 91
C     AW4 COMPUTES WATER BUDGET DAY 91 TO 145
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      COMMON NDO,MO,NYO
  100 FORMAT(3I8)
  101 FORMAT(2I4)
      READ (2,100)NDO,MO,NYO
      READ(2,101)N,M
      CALL EDAT
      CALL RDAT
      CALL FYLE
      CALL EXT
      DO 3 NYO=N,M
```

```
   CALL DATSW(1,J)
   GO TO (1,2),J
 1 STOP
 2 CONTINUE
   CALL RAYN
   CALL EVAP
   CALL PREP
   CALL WIN
   CALL AW1
   CALL AW2
   CALL AW3
   CALL AW4
 3 CONTINUE
   CALL EXIT
   END
```

```
// FOR
*ONE WORD INTEGERS
*LIST SOURCE PROGRAM
      SUBROUTINE EDAT
      DIMENSION EO(31),LM(12)
      DATA LM/31,28,31,30,31,30,31,31,30,31,30,31 /
      N=1
C****** IF WEATHER BUREAU FORMAT PUT IWB=1,FOR ATS FORMAT
C     IWB =0  (IWB..I10)
      READ(2,102)IWB
    1 CONTINUE
      IF(IWB)201,202,201
  201 READ(2,101)IY,M,EO
  101 FORMAT(7X,2I2,31F2.0)
      GO TO 204
  202 READ(2,203)IY,M,ND, (EO(III),III=1,ND)
  203 FORMAT(5X,3I2,4X,31F2.0)
  204 CONTINUE
      IF(IY)15,15,2
    2 DO 200 I=1,31
  200 EO (I)=EO(I)*0.254
      IF(M-2)6,4,6
    4 IY=IY+1900
      IF(IY-(IY/4)*4)60,5,60
    5 LLL=29
      IY=IY-1900
      GO TO 66
   60 IY =IY-1900
    6 LM (2)=28
      LLL=LM(M)
   66 WRITE(17'N)IY,M,LLL,(EO(I),I=1,LLL)
      WRITE(3,102)IY,M,LLL,(EO(I),I=1,LLL)
  102 FORMAT(3I10/15F6.1/16F6.1)
      N=N+1
      GO TO 1
   15 CONTINUE
      RETURN
      END
```

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
**  PROGRAM TO PREPARE RAINFALL DATA FOR ANALYSIS


C       REQUIREMENTS FOR FIRST CARD
C       --------------------------
C       IY PUNCHED IN COLUMNS 1 AND 2
C       IM PUNCHED IN COLUMNS 3 AND 4
C       IWB PUNCHED IN COLUMN 6
C       MILLE PUNCHED IN COLUMN 8
C       IY=INITIAL YEAR E.G. 63 , IM=INITIAL MONTH E.G. 04
C       IWB IS 01 FOR WEATHER BUREAU DATA,0 FOR NARI DATA
C       MILLE IS 00 FOR DATA IN INCHES, 01 FOR DATA IN MILL
C       IMETRES (NARI)
C       FOR WEATHER BUREAU DATA MILLE IS READ ON EACH DATA
C       CARD AND NEED NOT
C       BE SPECIFIED ON FIRST CARD
C       STATION NAME IS PUNCHED BETWEEN COLUMNS 10 AND 68

C       DATA CARDS
C       ----------
C       NARI DATA IS PUNCHED IN FORMAT 2I4,9(I4,F4.0)
C       WEATHER BUREAU DATA IS PUNCHED IN FORMAT  1XI1,6X
C       2I2,9(I2,F4.0)
C       THE FIRST VARIABLE READ ON W.B. DATA CARDS IS MILLE
C       LAST DATA CARD IS BLANK

        SUBROUTINE RDAT

        INTEGER DAYS(12),ID(9),NAME(30)
        REAL RAIN(31),LRAIN(31)
        DIMENSION R(31)
        DATA DAYS/31,28,31,30,31,30,31,31,30,31,30,31/,LRAIN/31*0./
        READ(2,100)IY,IM,IWB,MILLE,NAME
  100   FORMAT(4I2,30A2)
        IS=(IY-1)*12+IM
        DO 1 I=1,31
    1   RAIN(I)=0.
        IOUT=1
        MERR=0
        M1=1
    2   IF(IWB)3,3,4
    3   READ(2,101)IY,M,(ID(J),R(J),J=1,9)
  101   FORMAT(2I4,9(I4,F4.0))
        GO TO 5
    4   READ(2,102)MILLE,IY,M,(ID(J),R(J),J=1,9)
  102   FORMAT(1XI1,6X2I2,9(I2,F4.0))
        MILLE=MILLE-5
    5   IF(M-1)33,8,6
    6   IY=(IS-1)/12+1
        M1=IS-(IY-1)*12
        IS=IS+1
        IF(M1-1)33,7,34
```

```
 34 IF(M-M1)6,2,6
  7 IS=IS-1
    IC=IS-2
    GO TO 16
  8 IC=IS-2
    GO TO 21
  9 IF(IWB)10,10,11
 10 READ(2,101)IY,M,(ID(J),R(J),J=1,9)
    GO TO 12
 11 READ(2,102)MILLE,IY,M,(ID(J),R(J),J=1,9)
    MILLE=MILLE-5
 12 IF(M)30,30,13
 30 IOUT=2
    GO TO 16
 13 IF(M-12)15,15,14
 14 WRITE(3,103)IY,M,(ID(J),R(J),J=1,9)
103 FORMAT(10X'MONTH GREATER THAN 12 ON FOLLOWING CARD'/
   -10X2I4,9(I5,F5.0))
    MERR=1
    GO TO 9
 15 IF(M-M1)16,21,16
 16 IT=IS
    GO TO (31,35),IOUT
 31 M1=M
    GO TO 36
 35 M=LAST
 36 IYY=(IT-1)/12+1
    IMM=IT-12*(IYY-1)
    NDAS=DAYS(IMM)
    IF(IMM-2)19,17,19
 17 IF(IYY-IYY/4*4)19,18,19
 18 NDAS=29
 19 GO TO (39,37),IOUT
 37 IF(IMM-M)38,39,38
 38 WRITE(16'IT-IC)IYY,IMM,NDAS,LRAIN
    IT=IT+1
    GO TO 36
 39 WRITE(16'IT-IC)IYY,IMM,NDAS,RAIN
    IS=IS+1
    GO TO (40,27),IOUT
 40 DO 20 I=1,31
 20 RAIN(I)=0
    IT=M+12*(IY-1)
    IF(IT-IS)33,21,16
 21 LAST=M
    DO 26 I=1,9
    IF(ID(I))9,9,22
 22 L=ID(I)
    IF(L-31)24,24,23
 23 WRITE(3,104)IY,M,(ID(J),R(J),J=1,9)
104 FORMAT(10X'DAY GREATER THAN 31 ON FOLLOWING CARD'/
   -10X2I4,9(I5,F5.0))
    MERR=1
    GO TO 9
```

```
    9 NCW=NCW+1
      DO 11 I=1,10
      P(I)=II*0.1005
   11 II=II+1
      WRITE(3,101)( P(J),CASM(J) ,J=1,10)
    1 CONTINUE
C*****************************************************************
C       RUN-OFF
      DO 12 N=1,10
      II=1
      DO22 I=1,13
      READ (2,100)RR
      DO 2 J=1,10
      P(J)=II
      R(II)=RR(J)
      II=II+1
    2 CONTINUE
   22 WRITE(3,101)( P(J),RR(J),J=1,10)
   12 WRITE (13'N)R
      WRITE (3,102)
  102 FORMAT(//)
C*****************************************************************
C       ET/EO RATIO
      K=1
      NKF=1
      DO 4 N=1,15
      READ (2,103)E
      DO 112 I=1,10
      ND(I)=K
      IF(NKF-146)111,112,112
  111 WRITE(14'NKF)E(I)
      NKF=NKF+1
  112 K=K+1
    4 WRITE(3,104)( ND(J),E(J) ,J=1,10)
  103 FORMAT (10F8.3)
C*****************************************************************
C       ROOT PROGRESS
      K=1
      NRL=1
      DO 60 I=1,10
      READ(2,106)RT
  106 FORMAT(10F8.0)
      DO 61 J=1,10
      WRITE(6'NRL)RT(J)
      NRL=NRL+1
      ND(J)=K
   61 K=K+1
   60 WRITE(3,107)(ND(J),RT(J),J=1,10)
  107 FORMAT(10(I6,F6.0))
      DO 62 I=101,145
      RTT=1200.
   62 WRITE(6'I)RTT
      DO 65 I=1,4
      DO 64 II=1,10
      IK=100+10*(I-1)+II
      READ(6'IK)RT(II)
   64 ND(II)=IK
   65 WRITE(3,107)(ND(II),RT(II),II=1,10)
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

```
C       FASM
        READ(2,105)FASM
        WRITE(4'1)FASM
        READ(4'1)FASM
        WRITE(3,105)FASM
   105  FORMAT(4F8.2)
        RETURN
        END
```

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
        SUBROUTINE EXT
        DIMENSION E(4)
        WRITE(3,102)
   100  FORMAT (4 F8.0)
   102  FORMAT(5X'EXT')
        NEX=1
        DO 1 I=1,91
        READ(2,100)E
        WRITE(5'NEX)E
        NEX =NEX+1
     1  CONTINUE
        DO 2 I=1,91
        READ(5'I)E
     2  WRITE (3,100)E
        RETURN
        END
```

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
        SUBROUTINE RAYN
C       BEWARE.. CANNOT HAVE NDO,MO=(1-10),1(JANUARY)
C       NDO,MO=(1-10),3MARCH
        DIMENSION R(31),LNTH(12), RAN(12),NA(12)
        COMMON NDO,MO,NYO
        DATA LNTH/31,28,31,30,31,30,31,31,30,31,30,31/
        WRITE (3,105)NYO,MO,NDO
```

```
105 FORMAT(3I8)
    IF(NDO-10)120,120,121
120 MI=MO-1
    NDI=NDO+LNTH(MI)-10
    GO TO 122
121 NDI=NDO-10
    MI=MO
122 CONTINUE
    N=1
    NRD=1
    NN=1
  1 READ(16'NRD) NY,M,L,R
     NRD=NRD+1
    IF (NY-NYO)1,2,1
  2 IF(M-MI)1,3,1
  3 LENTH=LNTH(MI)
    DO 6 I=NDI,LENTH
    WRITE(11'N)R(I)
    IF(N-11)5,4,4
  4 WRITE(9'NN)R(I)
    N=N+1
    NN=NN+1
    GO TO 6
  5 N=N+1
  6 CONTINUE
  7 READ(16'NRD)NY,M,L,R
     NRD=NRD+1
    DO 11 I=1,L
    IF (N-155)8,8,11
  8 IF(N-11)10,9,9
  9 WRITE(9'NN)R(I)
    NN=NN+1
 10 WRITE(11'N)R(I)
    N=N+1
 11 CONTINUE
    IF (N -155)7,7,12
 12 KK=1
    DO 88 II=1,12
    DO 87 I=1,12
    K=(II-1)*12+I
    READ(9'K)RAN(I)
 87 NA(I)=K
 88 WRITE(3,102)(NA(J),RAN(J),J=1,12)
102 FORMAT(12(I6,F4.1))
    RETURN
    END
```

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
C      SUBROUTINE TO WRITE EVAP DATA TO DISK
       SUBROUTINE EVAP
       DIMENSION EO(31),EV(145)
       COMMON  NDO,MO,NYO
       K=1
       N=1
     1 READ(17'N)IY,M,LLL,EO
       N=N+1
       IF(NYO-IY)8,2,1
     2 IF(MO-M)8,3,1
     3 DO 4 I=NDO,LLL
       WRITE(8'K)EO(I)
       K=K+1
     4 CONTINUE
     8 READ(17'N)IY,M,LLL,EO
       N=N+1
       DO10I=1,LLL
       IF(K-145)9,9,10
     9 WRITE(8'K)EO(I)
        K=K+1
    10 CONTINUE
       IF(K-146)8,11,11
    11 X=1.
       DO 13 I=1,145
    13 READ (8'I)EV(I)
   103 FORMAT(10 F10.1)
       WRITE(3,103)(EV(K),K=1,145)
       RETURN
       END
```

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
       SUBROUTINE PREP
C      SUBROUTINE TO WRITE ETRAN AND CASM TO DISK
       DO 4 I=1,145
       READ(8'I)EO
       READ(14'I)EKF
       ET=EO*EKF
       WRITE (3'I)ET
       IF(EO-18.)101,101,100
   100 EO=18.
   101 CONTINUE
       IF(EO-.0005)1,1,2
     1 EO=0.1
     2 J=EO*10.+0.05
       READ(7'J)CASM
       WRITE(15'I)CASM
     4 CONTINUE
       RETURN
       END
```

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTFGERS
      SUBROUTINE WIN
C     SUBROUTINE TO CALCULATE WATER ENTERING SOIL
      DIMENSION RR(125),RRR(125)
C     EXECUTE DAY BY DAY
C     FIRST CALCULATING ANTECEDENT PRECIPITATION INDEX
      N=1
      DO 3 NN=1,145
      API=0.
      DO 1 I=1,10
      J=NN+I-1
      READ(11'J)P
      P=P/(11-I)
      API=API+P
    1 CONTINUE
      READ(9'N)P
      P=P/2.
      API=API+P
      WRITE(12'N)API
      N=N+1
    3 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C     CALCULATE RUNOFF
C     FIRST FILE IS APO
      DO 51 N=1,145
      READ(12'N)API
      IF (API-7.0)4,4,5
    4 J=2
      A1=0.0
      A2=7.0
      GO TO 50
    5 IF (API-12.5)6,7,7
    6 J=3
      A1=7.0
      A2=12.5
      GO TO 50
    7 IF(API-19.5)8,8,9
    8 J=4
      A1=12.5
      A2=19.5
      GO TO 50
    9 IF(API-25.0)10,11,11
   10 J=5
      A1=19.5
      A2=25.0
      GO TO 50
   11 IF(API-32.0)12,13,13
   12 J=6
      A1=25.0
      A2=32.0
```

```
      GO TO 50
   13 IF(API-37.5)14,15,15
   14 J=7
      A1=32.0
      A2=37.5
      GO TO 50
   15 IF (API-50.0)16,17,17
   16 J=8
      A1=37.5
      A2=50.0
      GO TO 50
   17 IF(API-62.5)18,19,19
   18 J=9
      A1=50.0
      A2=62.5
      GO TO 50
   19 J=10
      A1=62.5
      A2=75.0
   50 READ(13'J-1)RR
      READ(13'J)  RRR
      READ(9'N)RAIN
      IF(RAIN-124.9)24,24,23
   23 WRITE(3,101)N
  101 FORMAT(20X41('*')/20X'* ON THE'I4,'TH DAY
     -RAIN EXCEEDED 124.9   *'/
     *20X41('*'))
      RAIN = 124.
   24 K=RAIN + 1.
      RF=RR(K)
      RFF=RRR(K)
      R=RF+((API-A1)/(A2-A1)*(RFF-RF))
      READ(9'N)PPN
      WWW=PPN-R
   51 WRITE(1'N)WWW
      DO 52 I=1,145
      READ(12'I)API
      READ(9'I)PPN
      READ(1'I)WWW
   52 CONTINUE
      RETURN
      END
```

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTFGFRS
      SUBROUTINE AW 1
      DIMENSION ASMF(4),FASM(4)
      WRITE (3,100)
  100 FORMAT(1H1,10X'ASM IN TOP 150MM'/5X'DAY',5X'MM'//)
      READ (4'1)FASM
      ASM =12.
      DO 6 N=1,16
      READ(1'N)W
      W=W-2.5
      ASM = ASM+W
      IF(ASM - 12.)3,2,2
    2 ASM=12.
      GO TO 5
    3 IF(ASM)4,5,5
    4 ASM = 0.
    5 WRITE(3,101)N,ASM
  101 FORMAT(6XI2,5X,F5.1)
    6 CONTINUE
      ASMF(1)=ASM+13.
      DO 8 L=2,4
    8 ASMF(L)= FASM(L)
      WRITE(2'1)ASMF
      RETURN
      END
```

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINE AW2
       DIMENSION ASMF(4),FASM(4)
      READ(4'1)FASM
      READ(2'1) ASMF
      ASM=ASMF(1)
      WRITE(3,100)
  100 FORMAT(//10X'ASM IN TOP 300MM'/5X'DAY' 5X'MM'//)
      DO 1 N=17,28
      READ(1'N)W
       READ(3'N)ET
      ASM = ASM - ET+W
      IF (ASM-25.)4,2,2
    2 ASM=25.
      GO TO 6
    4 IF(ASM)5,6,6
    5 ASM=0.
    6 WRITE (3,101)N,ASM
  101 FORMAT(6XI2,5X,F5.1)
    1 CONTINUE
      ASMF(1)=ASM
      DO 8 L=2,4
    8 ASMF(L)=FASM(L)
      WRITE (2'1)ASMF
      WRITE(3,100)
      RETURN
      END
```

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINF AW3
      DIMENSION ASM(4),FASM(4),XS(4),           ASMT(4),EX(4),ADD(6)
  101 FORMAT(7X,I3,4F10.1,F10.3,F10.1,/60X,F10.1/60X,F10.1/60X,F10.1,
     *4F10.1,I10)
  102 FORMAT(1H1)
  103 FORMAT(5X' DAY '5X' API '5X'RAIN '5X' WIN '5X'EVAP '5X'ETRAN'5X
     *'SASM '5X'TASM '5X'PASM '5X'CASM '5X'COND ')
      WRITE(3,102)
      WRITE(3,103)
      READ(4'1)FASM
      DO 19 N=29,91
      READ(1'N)W
      READ(2'1)ASMT
      READ(3'N)ET
      READ(5'N)EX
      READ(6'N)RL
      READ(8'N)EO
      READ(12'N)API
      READ(15'N)CASM
      DO 2 L=1,4
      ADD(L)=0.
    2 XS(L)=0.
      TXS=0.
      DO 3 L=1,4
    3 EX (L) = EX(L)*ET/100.
      ASM(1)=ASMT(1)-EX(1)
C     IF LAYER IS DRY TRANSFER DEMAND
      IF (ASM(1)) 4,5,5
    4 XS(1) =-1.*ASM(1)
      ASM(1)=0.+W
      ADD(2)=0.
      GO TO 8
    5 XS(1)=0.
C     IF NOT DRY TRANSFER ADD TO LOWER
      IF (ASM(1) - 25.) 80,6,6
   80 ASM(1) = ASM(1) + W
      GO TO 8
    6 ADD(2)=ASM(1)-25.
      IF(ADD(2)-25.)88,7,7
   88 ASM(1) = 25. + W
      GO TO 8
    7 ADD(2)=25.
      ASM(1) = ASM(1) - 25. + W
C     REPEAT FOR LOWER LAYERS
    8 DO 113 L= 2,4
      ASM(L) = ASMT(L) - EX(L)
      IF(ASM(L))9,10,10
    9 XS(L)=-1.*ASM(L)
      ASM(L)=0.+ADD(L)
```

```
      ADD(L+1)=0.
      GO TO 113
  10  XS(L)=0.
      IF(ASM(L)-FASM(L))13,11,11
  11  ADD(L+1)=ASM(L)-FASM(L)
      IF (ADD(L+1)-FASM (L))110,111,111
 110  ASM(L) = FASM(L) + ADD(L)
      GO TO 113
 111  ASM(L) = ADD(L+1) + ADD(L)
      ADD(L+1)=FASM(L)
      GO TO 113
  13  ADD(L+1)=0.
      ASM(L) = ASM(L) + ADD(L)
 113  CONTINUE
      DO 14 L=1,4
  14  TXS =TXS+XS(L)
      DO 17 L=1,4
      ASM(L)=ASM(L)-TXS
      IF(ASM(L))15,16,16
  15  TXS=-1.*ASM(L)
      ASM(L)=0.
      GO TO 17
  16  TXS=0.
  17  CONTINUE
      TASM=0.
      FC=0.
      RLL=RL/300.
      IL=RLL
      PU=RLL-IL
      LO=IL+1
      IF(LO-5)301,300,300
 300  LO=4
       PU=1.
 301  DO114 L=1,LO
      P=1.
      IF(L-LO)303,302,303
 302  P=PU
 303  TASM=TASM+P*ASM(L)
      FC=FC+P*FASM(L)
 114  CONTINUE
      PASM = TASM/FC*100.
      IF (PASM-CASM    )201,201,202
 201  ST =1
      DO 20 L=1,4
      ADD(L)=0.
  20  CONTINUE
      ASM(1) = ASMT(1)
      ADD(2)=ASM (1)-FASM(1)
      IF (ADD(2))220,220,221
 220  ADD(2)=0.
      ASM(1) = ASM(1) + W
      GO TO 224
 221  IF(ADD(2)-FASM(1))222,223,223
 222  ASM(1) = FASM(1) + W
```

```
      GO TO 224
  223 ADD(2)=FASM(1)
      ASM(1) = ASMT(1) - FASM(1) + W
  224 DO 228 L=2,4
      ASM(L) = ASMT(L)
      ADD(L+1)=ASM (L)-FASM(L)
      IF (ADD(L+1))225,225,226
  225 ADD(L+1)=0.
      ASM(L)=ASM(L)+ADD(L)
      GO TO 228
  226 IF (ADD(L+1)-FASM(L))2228,227,227
 2228 ASM(L) = FASM(L) + ADD(L)
      GO TO 228
  227 ADD(L+1)=FASM(L)
      ASM(L) = ASMT(L) - FASM(L) + ADD(L)
  228 CONTINUE
      DO 229  L=1,4
      ASMT(L)=ASM(L)
  229 CONTINUE
      WRITE(2'1)ASMT
      GO TO204
  202 ST=0.
      DO 24 L = 1,4
   24 ASMT (L) = ASM(L)
      WRITE(2'1)ASMT
  204 READ (9'N)R
      WRITE(3,101)N,API,R,W,EO,ET,(ASM(J),J=1,4),TASM,PASM,CASM,ST
      WRITE(10'N)TASM
   19 CONTINUE
      RETURN
      END
```

```
// FOR
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINE AW4
      DIMENSION ASM(4),FASM(4),XS(4),          ASMT(4),EX(4),ADD(6)
  101 FORMAT(7X,I3,4F10.1,F10.3,F10.1,/60X,F10.1/60X,F10.1/60X,F10.1,
     *4F10.1,I10)
  102 FORMAT(1H1)
  103 FORMAT(5X' DAY '5X' API '5X'RAIN '5X' WIN '5X'EVAP '5X'ETRAN'5X
     *'SASM '5X'TASM '5X'PASM '5X'CASM '5X'COND ')
      WRITE(3,102)
      WRITE(3,103)
      READ(4'1)FASM
      DO 1019 N=92,145
      EX(1)=60.
      EX(2)=15.
      EX(3)=15.
      EX(4)=10.
```

```
      READ(1'N)W
      READ(2'1)ASMT
      READ(3'N)ET
      READ(6'N)RL
      READ(8'N)EO
      READ(12'N)API
      READ(15'N)CASM
      DO 2 L=1,4
      ADD(L)=0.
    2 XS(L)=0.
      TXS=0.
      DO 3 L=1,4
    3 EX (L) = EX(L)*ET/100.
      ASM(1)=ASMT(1)-EX(1)
C     IF LAYER IS DRY TRANSFER DEMAND
      IF (ASM(1)) 4,5,5
    4 XS(1) =-1.*ASM(1)
      ASM(1)=0.+W
      ADD(2)=0.
      GO TO 8
    5 XS(1)=0.
C     IF NOT DRY TRANSFER ADD TO LOWER
      IF (ASM(1) - 25.) 80,6,6
   80 ASM(1) = ASM(1) + W
      GO TO 8
    6 ADD(2)=ASM(1)-25.
      IF(ADD(2)-25.)88,7,7
   88 ASM(1) = 25. + W
      GO TO 8
    7 ADD(2)=25.
      ASM(1) = ASM(1) - 25. + W
C     REPEAT FOR LOWER LAYERS
    8 DO 113 L= 2,4
      ASM(L) = ASMT(L) - EX(L)
      IF(ASM(L))9,10,10
    9 XS(L)=-1.*ASM(L)
      ASM(L)=0.+ADD(L)
      ADD(L+1)=0.
      GO TO 113
   10 XS(L)=0.
      IF(ASM(L)-FASM(L))13,11,11
   11 ADD(L+1)=ASM(L)-FASM(L)
      IF (ADD(L+1)-FASM (L))110,111,111
  110 ASM(L) = FASM(L) + ADD(L)
      GO TO 113
  111 ASM(L) = ADD(L+1) + ADD(L)
      ADD(L+1)=FASM(L)
      GO TO 113
   13 ADD(L+1)=0.
      ASM(L) = ASM(L) + ADD(L)
  113 CONTINUE
      DO 14 L=1,4
   14 TXS =TXS+XS(L)
      DO 17 L=1,4
      ASM(L)=ASM(L)-TXS
      IF(ASM(L))15,16,16
```

```
 15 TXS=-1.*ASM(L)
    ASM(L)=0.
    GO TO 17
 16 TXS=0.
 17 CONTINUF
    TASM=0.
    FC=0.
    RLL=RL/300.
    IL=RLL
    PU=RLL-IL
    LO=IL+1
    IF(LO-5)301,300,300
300 LO=4
     PU=1.
301 DO114 L=1,LO
    P=1.
    IF(L-LO)303,302,303
302 P=PU
303 TASM=TASM+P*ASM(L)
    FC=FC+P*FASM(L)
114 CONTINUE
    PASM = TASM/FC*100.
    IF (PASM-CASM   )201,201,202
201 ST =1
    DO 20 L=1,4
    ADD(L)=0.
 20 CONTINUE
    ASM(1) = ASMT(1)
    ADD(2)=ASM (1)-FASM(1)
    IF (ADD(2))220,220,221
220 ADD(2)=0.
    ASM(1) = ASM(1) + W
    GO TO 224
221 IF(ADD(2)-FASM(1))222,223,223
222 ASM(1) = FASM(1) + W
    GO TO 224
223 ADD(2)=FASM(1)
    ASM(1) = ASMT(1) - FASM(1) + W
224 DO 228 L=2,4
    ASM(L) = ASMT(L)
    ADD(L+1)=ASM (L)-FASM(L)
    IF (ADD(L+1))225,225,226
225 ADD(L+1)=0.
    ASM(L)=ASM(L)+ADD(L)
    GO TO 228
226 IF (ADD(L+1)-FASM(L))2228,227,227
2228 ASM(L) = FASM(L) + ADD(L)
    GO TO 228
227 ADD(L+1)=FASM(L)
    ASM(L) = ASMT(L) - FASM(L) + ADD(L)
228 CONTINUF
    DO 229  L=1,4
    ASMT(L)=ASM(L)
```

```
 229 CONTINUE
     WRITE(2'1)ASMT
     GO TO204
 202 ST=0.
     DO 24 L = 1,4
  24 ASMT (L) = ASM(L)
     WRITE(2'1)ASMT
 204 READ (9'N)R
     WRITE(3,101)N,API,R,W,EO,ET,(ASM(J),J=1,4),TASM,PASM,CASM,ST
     WRITE(10'N)TASM
1019 CONTINUE
     RETURN
     END
```