Proceedings

Agroclimatological Research Needs of the Semi-Arid Tropics

International Crops Research Institute for the Semi-Arid Tropics

Proceedings of the

International Workshop on the Agroclimatological Research Needs of the Semi-Arid Tropics

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Publication Editor

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Preface

In the semi-arid tropics high and sustained agricultural production is hampered by many natural constraints. The SAT farmer must cope with the vagaries of a rainy season that is short and highly unpredictable; intense rainfall interspersed with sudden droughts; soils with low infiltration capacity and thus great water erosion hazard; and, finally, a high evapotranspiration rate during the growing season.

In 1973, ICRISAT began its program to develop farming systems that will help increase and stabilize agricultural production through better use of natural, human, and capital resources in the semi-arid tropics. Within this main program, the agroclimatology subprogram deals with the characterization and quantification of weather elements (and climate) in relation to agriculture. Following 5 years of research in this area, ICRISAT sponsored an International Workshop on the Agroclimatological Research Needs of the Semi-Arid Tropics.

The main objectives of the workshop are:

1. To discuss the current status of agroclimatological research at ICRISAT and in the semi-arid tropics in Asia, Africa, South America, and Australia, specifically:
   a. Present techniques and approaches in the investigations of physical resources in the semi-arid tropics.
   b. Available instrumentation for data collection, its accuracy and adequacy.
   c. Available methods for the quantification of moisture environment and its application in crop planning.
2. To suggest and plan a future course of action for climatological research, with major emphasis on:
   a. Modifying or expanding the present approaches so that the results may be targeted and information disseminated within a given time scale.
   b. Planning crop-weather interaction studies that may be set up at bench-mark locations around the semi-arid tropics.
   c. Establishing research links that will aid in improving the present data base and its analysis.

The 24 participants included scientists from Australia, Brazil, Canada, France, India, Kenya, Niger, Senegal, the United States of America, and Upper Volta, and representatives of the World Meteorological Organization, the Food and Agriculture Organization, and the U.S. Agency for International Development. Twenty ICRISAT staff also participated.

Four technical sessions were held: (1) Climatological features of the SAT discussed the agrometeorological network and data collection over the semi-arid areas of India, Brazil, and Africa; (2) Water-budgeting models and their application focused on studies related to thedynamics of soil moisture in

Vertisols and Alfisols, soil moisture budgeting techniques and their application; (3) Crop-environmental interactions aimed at identifying plant and atmospheric parameters in water-stress studies in relation to their effect on plant growth and yield; and (4) Interdisciplinary research needs of agroclimatological studies at ICRISAT.

The summaries and recommendations of these sessions are presented at the beginning of each section of this volume.

ICRISAT is pleased to publish the proceedings of the International Workshop, which enabled our scientists and agroclimatologists from other SAT areas to share their views and benefit from one another's experience.

S. M. Virmani
Workshop Coordinator

Session 1

Climatological Features of the SAT: Methodologies and Techniques of Characterization

Chairman: W. Baier
Co-chairman: J. Ian Stewart

Rapporteur: M. V. K. Sivakumar

Summary and Recommendations

Summary of Papers

This session dealt with the importance of collecting good agrometeorological data for agroclimatological research in the semi-arid tropics and with the problems encountered in the acquisition of such data. The use of such data in agronomically relevant classifications of the climate was discussed. Examples of new approaches to a more meaningful interpretation of climatological data in agricultural research, development, and operations were presented. Status reports of the agrometeorological services for portions of Africa, Brazil, and India were presented.

Dr. Virmani pointed out that the SAT is a unique region, where temperatures are generally adequate, with lack of moisture as the key limiting factor. Methods for quantifying rainfall distribution, thesoil moisture environment, and water balance methodology were discussed. He emphasized the usefulness of the ET/Ep ratio in analyzing crop-weather relationships. Similar expressions should be effective in crop-production models and in improved agroclimatic classifications to identify soil-crop-climate systems.

Dr. Rijks in his paper demonstrated the use of near real-time agrometeorological data in operational AGMET reports. He pointed out the need for standardization of observations and the importance of rapid dissemination of the information. He also referred to the program now under way at the Regional Agrhymet Center for training different types of personnel, and the Center's research and data analysis activities.

The need for international as well as national coordination of agrometeorological data collection became quite obvious from the paper by Dr. Reis, who reviewed the meteorological networks and current studies in Northeast Brazil by various organizations.

Dr. Sarker presented a status report on the activities of the Agricultural Meteorology Division of the India Meteorological Department. The processed agrometeorological data are used in research, for example, in preparing crop-weather diagrams, crop-weather calendars, and the agroclimatic atlas. Awide range of rainfall analyses have been made to help define the water status of different zones in India. Crop-weather relationships have been established, which permit crop yield forecasts to be mafde. Pertinent weather information is currently provided to farmers through radio stations.

Finally, Dr. J. S. Russell presented and demonstrated the application of pattern analysis methods in agrometeorological research. This new approach to classifying climates, groupings of locations and extrapolation of experimental results appears to be a promising research tool supplementing present methods.

Recommendations

1. Steps need to be taken to integrate agrometeorological techniques, which provide information on the day-by-day soil-crop-atmosphere status, especially crop water stress, into studies concerned with the production of crops in different environments.
2. The specific requirements of agriculture for agrometeorological data need to be provided to national agrometeorological services (the India Meteorological Department, or IMD, in India).
3. National meteorological services should be requested to give high priority to the development of effective system for collecting and distributing agrometeorological data.
4. The application of new analytical approaches to analyzing crop-weather data and classifying climates for expediting the transfer of agrotechnology should be encouraged.

Climatological Features of the Semi-Arid Tropics in Relation to the Farming Systems Research Program

S. M. Virmani, M. V. K. Sivakumar, and S. J. Reddy*

Summary

The semi-arid tropics pose a unique set of climatic features to those involved in programs of agricultural development. Such areas, on the basis of temperature, are suitable for the production of any crop that does not require a cold period in its life cycle. Lack of moisture is the key limiting factor to stabilized and improved agriculture in SAT regions. In recent years, there has been a growing appreciation of these climatic constraints, and attempts are being made to increase the length of the growing period by improving soil and water management. Efforts to this end will involve the fitting of appropriate cropslcultivars to appropriate soil-climatic zones. In the SAT environment this would primarily mean the matching of moisture environment available to the water needs of the crop plants.

In this paper, methods for quantifying rainfall distribution; the moisture-availability environment as affected by moisture-storage capacity of the soils in relation to timeand quantum distribution of precipitation via water-balance methodology are presented. A scheme for matching the crop-water demand and stochastic water supply is presented for determining the "likely" suitability of crops to soil-rainfall environments.

Due to the characteristic spatial distribution of natural endowments in the tropical regions, the moisture environment for crop growth tends to be highly location specific. The methodology of integrating rainfall, soil storage, and evaporation characteristics via the water-balance procedure would greatly assist in the transfer of farming systems technology. Given the variability of the SAT, such a quantification also contributes substantially to delineating the potentially rewarding areas for agricultural research.

In the seasonally dry rainfed semi-arid tropics (SAT), crop yields are low and variable from year to year. The instability in agricultural production is caused primarily by undependabie rainfall. In any particular agroclimatic region, therefore, the aim of an interdisciplinary farming systems research team is to derive a set of practices for resource development, resource management, and utilization that will lead to substantial and sustained increases in agricultural production while conserving and improving the region's resource base.

The main focus of the Farming Systems Research Program at ICRISAT is "resource-centered" for increasing and stabilizing agricultural production in the SAT. The Agricultural Climatology subprogram is concerned primarily with resource assessment and classification. The distinctive characteristics of the SAT environment influence the distribution of natural endowments — soils, rainfall, and climate. It tends to introduce a strong element of location specificity in terms of the agricultural environment. Therefore, the quantification and characterization of the natural resource base of any SAT area is of fundamental importance for the transfer of agrotechnology. Given the variability of the SAT environment over time and space, such a quantification also contributes substantially in delineating the potentially most rewarding areas for agricultural research.

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Characteristics of the SAT Environment

The semi-arid tropics are characterized by a high climatic water demand. The mean annual temperature is >18°C and rainfall exceeds evapotranspiration for only 2 to 4.5 months in the dry and for 4.5 to 7 months in the wet/dry semi-arid tropics (Troll, 1965). In order to meet the high climatic water demand during the growing season, the study of the supply pattern of water assumes great importance. SAT regions are characterized by a highly variable rainfall. The coefficient of variability of rainfall in humid climates is about 10 to 20%, whereas in SAT climates it is 20 to 30%.

Rainfall Pattern of Hyderabad: an Example

The annual rainfall at Hyderabad is highly erratic, and data of the last 77 years (Fig. 1) show that it may vary from 320 mm (1972) to 1400 mm (1917). The variability is encountered inter-yearly as well as seasonally. Rainfall distribution during 1975, 1976, and 1977 at ICRISAT Center is plotted in Figure 2. It appears that distribution of seasonal rainfall is highly erratic, for example, September was the wettest month in 1975 and the driest month in 1977. In 1977, August received fairly good amounts of rainfall; in 1975, it was the driest of the rainy months. We observed that open-pan evaporation is highly influenced by rainfall. The values go down to as low as 3 mm on rainy days, and very high values of open-pan evaporation were recorded during dry days.

Effect of Atmospheric Demand on Soil-Moisture Availability

At this stage it may be pertinent *to* consider

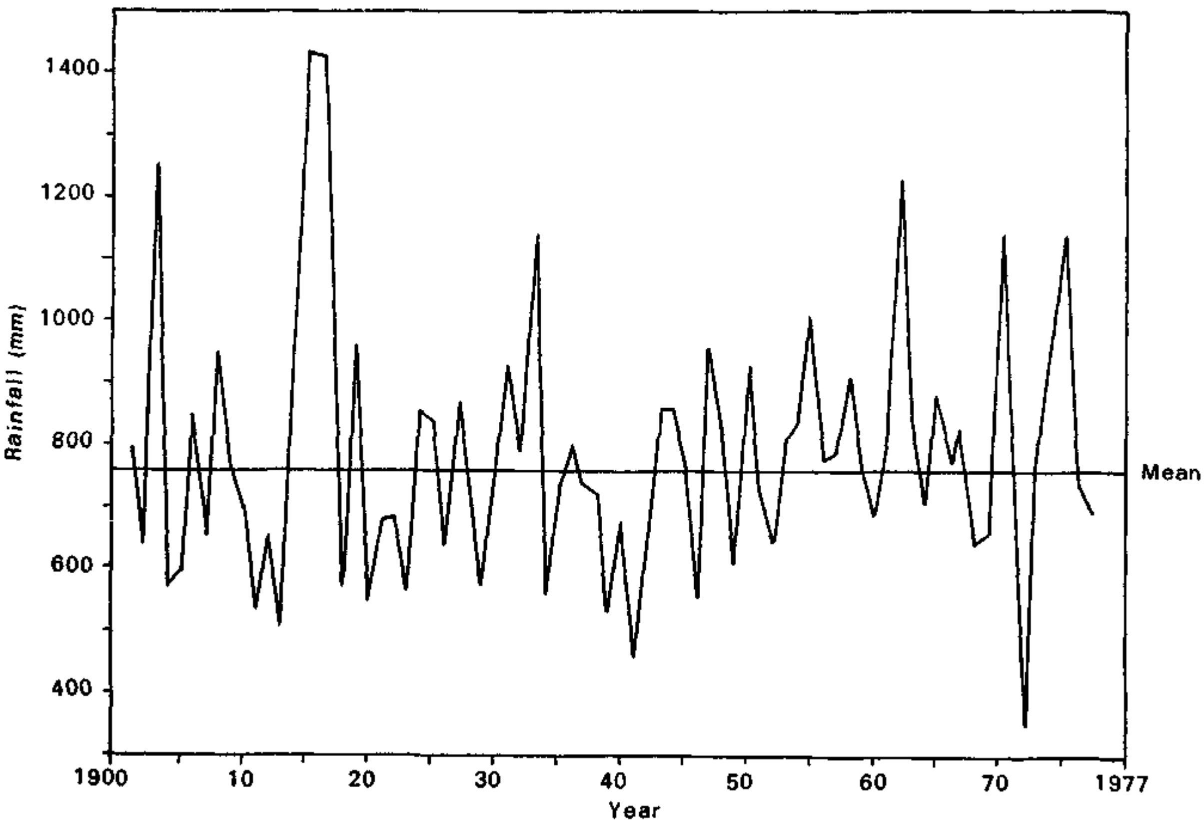


Figure 1. Annual rainfall at Hyderabad (1901-1977) (C. V. % : 26).

some of the environmental characteristics that are important in relation to supply and demand of soil moisture. The work of Denmead and Shaw (1962) and Shaw (1978) showed that the ability of soil to supply water to a crop is influenced by soil-moisture status and atmospheric evaporative demand. As shown in Table 1, the volumetric moisture content and atmospheric demand play an important role in determining the ratio of the actual supply of water to the potential water supply (termed relative rate of ET). If the volumetric soil moisture is about

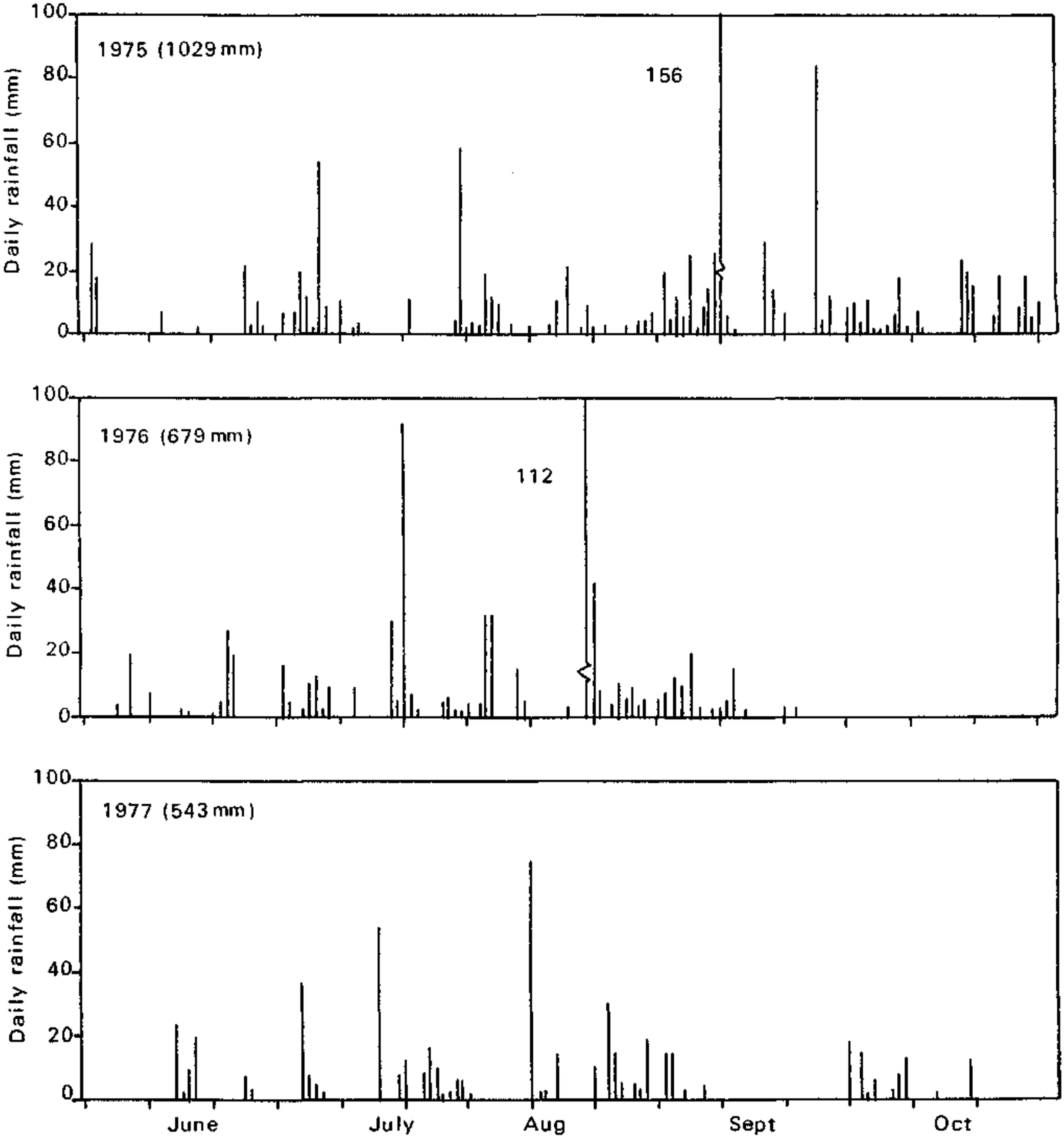


Figure 2. Rainfall distribution at ICRISAT Center, 1975 to 1977.

field capacity, then (irrespective of the potential evapotranspiration demand) the plants will be able to absorb water at a potential rate. If, on the other hand, volumetric soil moisture content drops down to 30%, the plants will be able to take up water at a potential rate only at low atmospheric-demand rates. At high evaporation rates the supply to plants will be only six-tenths of the potential demand. Thus the plants will be suffering from moisture stress even though about one-third of the available water is present in the root zone. Crop yields are proportional to the moisture availability and an optimum range of moisture-availability conditions is required for different crops, according to their growth pattern, for maximum yield. Hence (a) quantification of moisture environment for crop growth and (b) crop response to moisture stress and crop water needs are the major areas of concern to the ICRISAT agroclimatology research program.

Table 1. Relative rate of ET under three atmospheric-demand conditions.

Available soil moisture (% by volume)	Atmospheric demand		
	High	Medium	Low
100 (F.C.)	1.0	1.0	1.0
70	1.0	1.0	1.0
50	0.95	1.0	1.0
30	0.62	0.85	0.97
10	0.20	0.28	0.65

Source: Shaw, Modeling crop yields using climatic data. (This volume.)

Rainfall Climatology Research and Its Application

Let me discuss some of the methodologies and approaches that have been adopted at ICRISAT for investigation of climatic water availability. Let us look at some of the methods commonly used for determining climatic water availability, taking the Hyderabad region as an example (Table 2). The ratio of mean rainfall to potential evapotranspiration shows that rainfall could meet about 55% of the demand in the month of June, whereas in the subsequent rainy months rainfall adequately meets the demand (.85-1.37). August and September show a positive moisture balance. In the postrainy season, rainfall is not adequate to meet potential demand.

The mean monthly rainfall data do not yield information on the dependability of precipitation to meet potential demand. Hargreaves (1975) has defined dependable precipitation (DP) as that amount of rainfall which could be received at 75% probability. It is evident that the

Table 2. Climatic water availability at Hyderabad, India.

Month	Mean rainfall (mm)	Mean PE (mm)	RF/PE	Dependable precipitation (mm)[a]	MAI[b]
Jan	2	110		0	
Feb	10	129		0	
Mar	13	181		0	
Apr	23	198		6	.03
May	30	220		7	.03
Jun	107	196	0.55	59	.32
Jul	165	140	0.85	121	.75
Aug	147	135	1.09	86	.55
Sep	163	119	1.37	91	.65
Oct	71	124	0.57	30	.21
Nov	25	104	0.24	0	
Dec	5	99		0	

a. At 75% probability, also referred to as DP.
b. Moisture Availability Index = PD/PE

dependable precipitation amounts are much lower than the mean rainfall received at Hyderabad, and so one must consider dependable precipitation rather than mean rainfall. The moisture-availability index — defined as the ratio of dependable precipitation to mean rainfall — shows that adequate moisture is available for the rainy months of July, August, and September at Hyderabad. These analyses, however, do not give information on the continuity or breaks in rainfall and its adequacy to meet environmental demand on a short-term basis.

Probabilities of rainfall at Hyderabad as a function of time during the year are plotted in Figure 3. It is seen that in the dry months of January to June there is little chance of receiving an amount of rainfall that would be adequate to satisfy at least a third of the potential demand. But starting from the last week of June, these probabilities exceed the 70% level. The figure also shows that the onset of rainfall at Hyderabad is abrupt and that there is also a continuity in the rainfall once the rains begin. The continuity is depicted by the dotted line, which is a plot of the probability of a rainy week followed by a rainy week (wet/wet). The plot also shows another interesting feature in that rainfall receipts to meet at least one-third of the potential demand are fairly adequate throughout the months of July and September. In the month of August, however, a drought may be encountered in about 40% of the years. After October these probabilities again start going down, due to recession of monsoon rains.

Comparison of Rainfall Pattern of Two Locations

In order to illustrate the effectiveness of this kind of methodology in delineating some of the important precipitation features of site specificity and also to investigate whether the technology generated at ICRISAT Center can be transferred to another place, two locations fairly similar in their broad agroclimatic characteristics were selected (Hyderabad and Sholapur, Fig. 4). From their moisture-availability indices (Table 3), it is apparent that annual rainfall is fairly similar at both locations, as is seasonal rainfall. The rainfall is equally variable and the potential evapotranspiration is fairly similar at the two locations. The moisture-availability index calculated by Thornthwaite's method shows -56 for Hyderabad, but -58 for Sholapur. The growing season, as calculated by the approach of Cocheme and Franquin (1967), shows that Hyderabad has a growing period of about

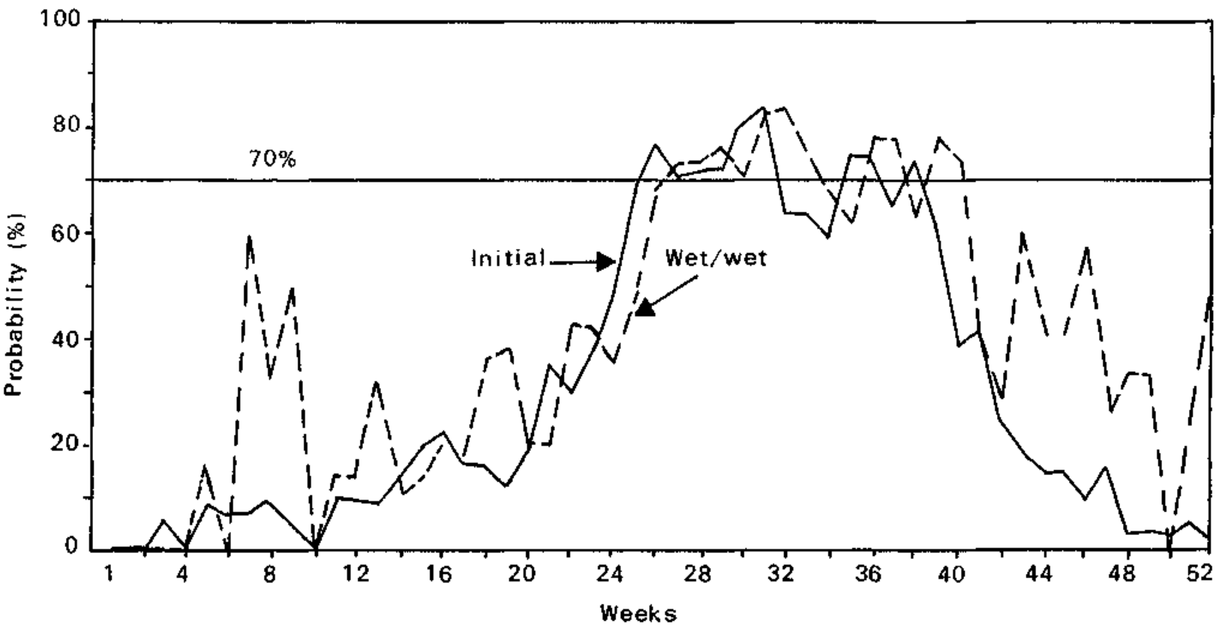


Figure 3. Probabilities of rainfall (RIPE≥ 0.33) at Hyderabad (1901-1970 data).

130 days, whereas at Sholapur the growing season could extend to 148 days. Both locations have deep Vertisols.

From the above, one would probably anticipate that the agricultural possibilities at the two locations are fairly similar. Five years of research, however, shows that rainy-season crops are successful at Hyderabad and the annual yields range from 5000 to 7000 kg/ha, while at Sholapur rainy-season crops are risky and annual yields range from 1000 to 2000 kg/ha. How does one explain such large differences in crop yields when the climatic characteristics of the two places are, on a very broad scale, fairly similar?

The reason can be seen from the plot of the

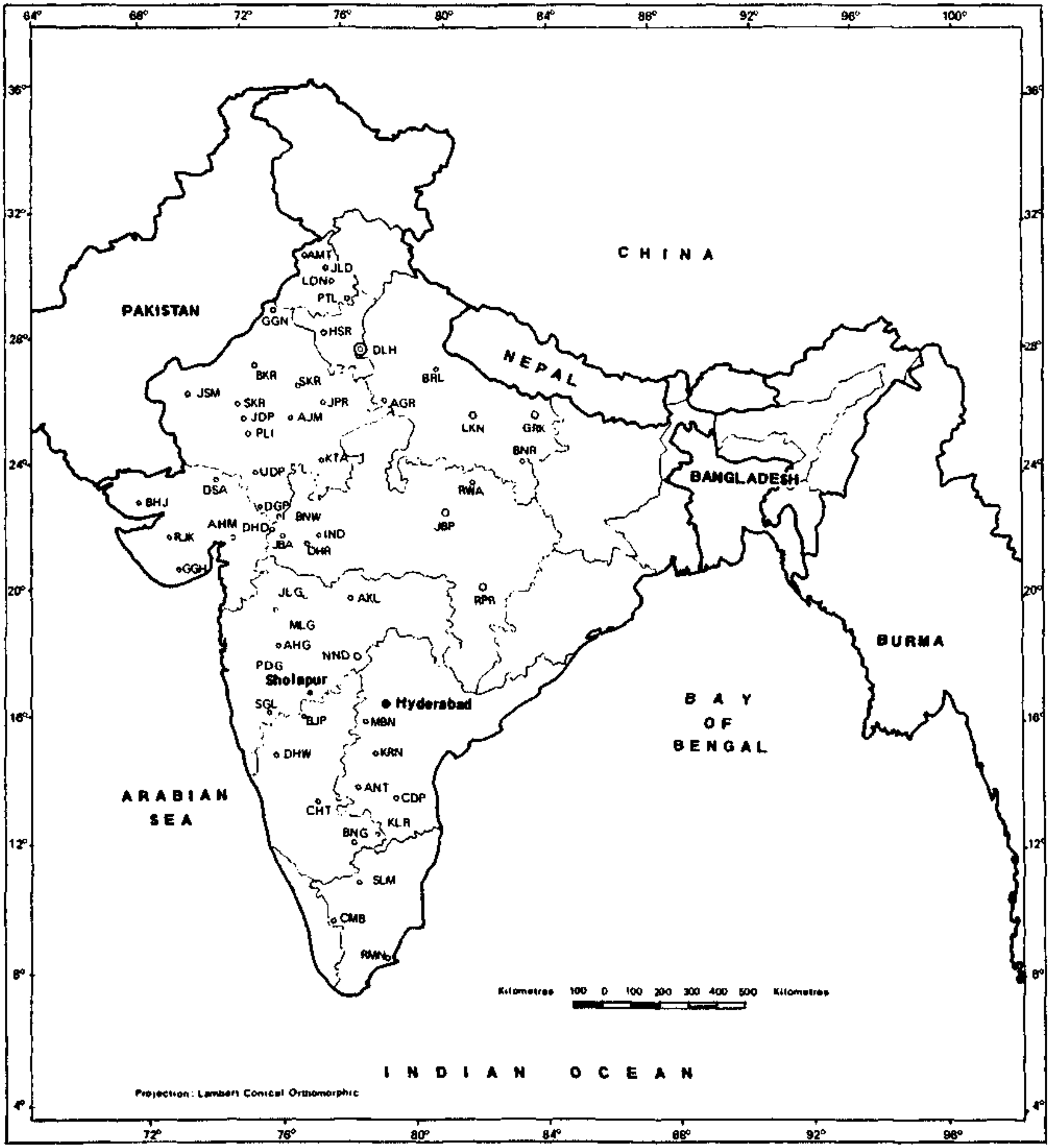


Figure 4. Location of Sholapur and Hyderabad.

Table 3. Moisture availability indices at two locations.

Index		Hyderabad	Sholapur
Annual	RF (mm)	764	742
Seasonal	RF (mm)	580	556
CV	RF (%)	26	28
PE	(mm)	1757	1802
I_m		-56	-58
Growing season (days)		130	148
Soils		Vertisols	Vertisols

a. Moisture index.

initial probabilities that rainfall will meet at least one-third of the potential demand at Hyderabad and Sholapur (Fig. 5). At Hyderabad, once rainfall begins, there is continuity of rainfall and a high degree of dependability throughout the months of July, August, and September. At Sholapur (the dotted lines) the continuity seen in rainfall at Hyderabad is not so obvious. At Sholapur, the rains are highly erratic during the growing season; hence the success of a rainy season crop is highly unpredictable. The continuity of the rains depicted by the conditional probabilities in Figure 6 (the probability of receiving a rain this week if the previous week

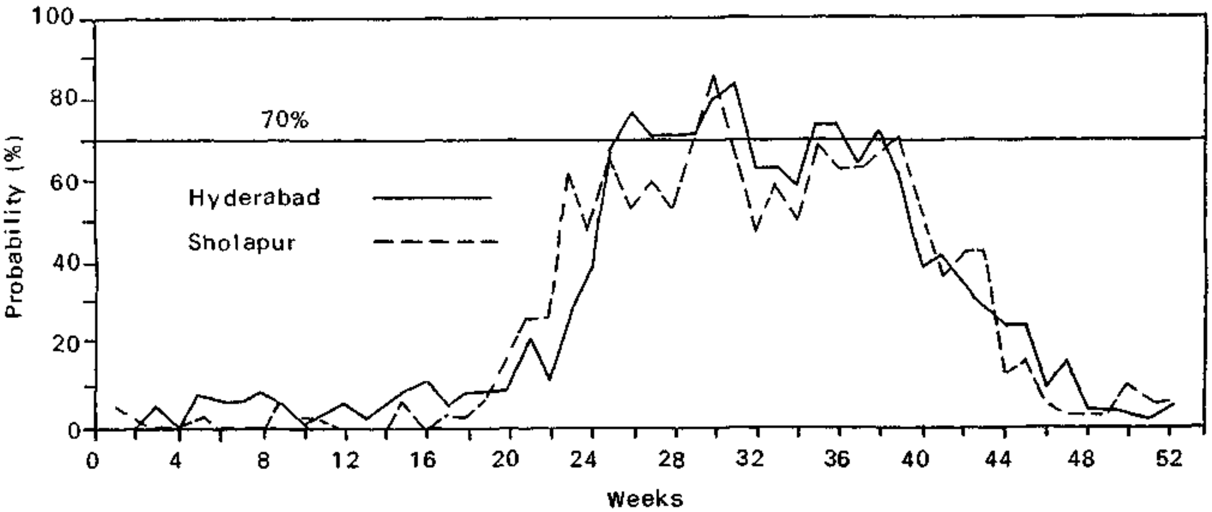


Figure 5. Initial probabilities of rainfall of RIPE≥ 0.33 at Hyderabad and Sholapur.

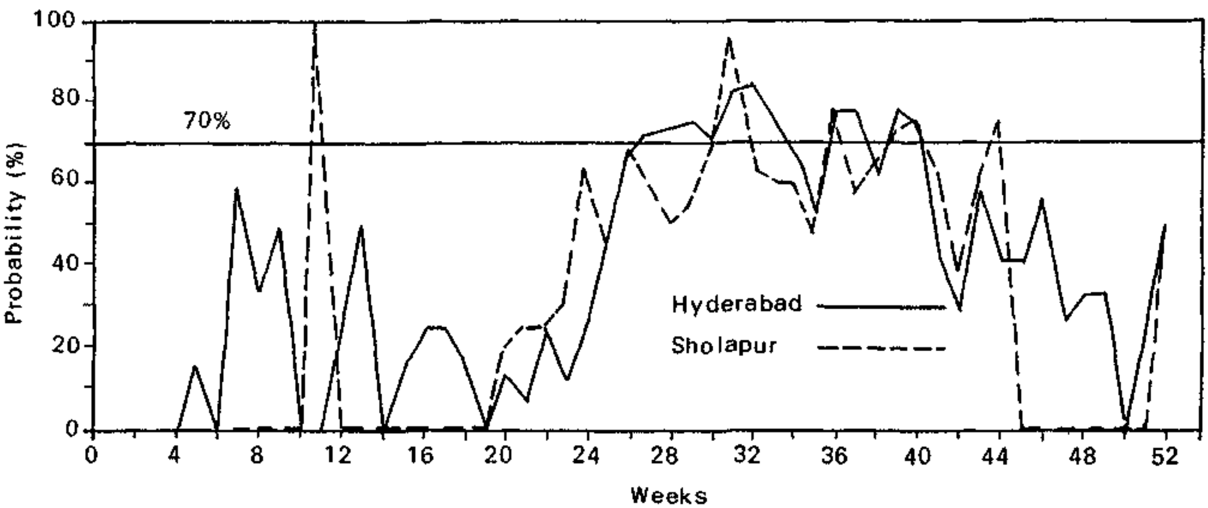


Figure 6. Conditional (wetlwet) probabilities of rainfall (RIPE>0.33) at Hyderabad and Sholapur.

has been wet) shows that at Hyderabad the continuity in rainfall is fair, whereas at Sholapur the continuity is less reliable.

One application of such analyses is to delineate the probability of success of different types of crops. Our studies on the relationship between dependable rainfall and suitability of crops for selected locations in India show that in areas with a high dependability of rainfall (e.g., Varanasi) the growing season is about 14 weeks at the 70% probability level. Dryland determinate crops could be successfully grown at this location. At Bangalore, on the other hand, even if one chooses a lower probability level of 60%, only indeterminate crops could be grown.

This methodology of rainfall probabilities could also be used to demarcate the risk associated with dry seeding of rainy-season crops in the SAT. The dry-seeding period for rainy-season crops will be a couple of weeks ahead of the onset of the rainy season. At Hyderabad, the onset of seasonal rainfall is abrupt at the commencement of the rainy season and the probabilities of continuance of rain are high. Therefore this location offers excellent scope for dry seeding. At Sholapur on the other hand, the onset of rains at the commencement of the season is not marked and the chances of the continuity of rains after onset are not as high. Such locations therefore pose a risk to dry seeding. Based on rainfall-probability analysis of more than 90 stations in India, the areas offering possibilities of dry seeding on Vertisols are mapped in Figure 7. Again the methodology is to use the dependability of precipitation and soil-moisture storage. It appears that one could distinguish very easily the risk associated with dry-seeding possibilities at different locations in the deep Vertisols spread over large areas in India. For example, the technology for dry seeding of crops generated at ICRISAT Center could be translated with a fair degree of success to Akola, Jabalpur, Indore, and Udaipur, whereas at Sholapur, Dharwar, Jalgaon, and Ahmedabad the likely success of dry seeding is low due to the high risk associated with it.

Stochastic Modeling Using the Water Balance Approach

So far, our discussion has been mainly on the probabilities of rainfall and the methodologies that may be used to employ this information in the planning of agricultural strategies/ operations. One other important component that affects length of the growing season is the water-holding capacity of the soils. The average pattern of changes in profile moisture on a weekly basis in three typical soils of Hyderabad region are plotted in Figure 8. These curves are based on rainfall records from 1901 through 1970. From water-balance analysis carried out as per CSIRO systems (Keig and McAlpin 1974), it is apparent that in shallow Alfisols there is very little soil-moisture storage for crop use over extended drought periods. In deep Alfisols and medium Vertisols, as well as in deep Vertisols, there is a fair degree of storagefor a fairly longer time during the growing season. Thus, under identical rainfall conditions, the effects of short-term intraseasonal droughts on crop-moisture status will differ in thethree soil types. The amount of water lost as runoff would also differ, and the potential benefits derived from supplemental applications of water would vary with the soil type.

Through water-balance studies, the length of the growing season for different soils can be estimated. The length of the growing season would depend *on* the available water-storage capacity of the soil (Table 4). At 75% probability level in soils with relatively low water-storage capacity under Hyderabad conditions, we have 15 weeks of growing season. Under high soil water-storage conditions, the growing season could be extended to about 23 weeks. This would mean that (depending on soil water-storage capacity) one could grow a medium- to a long-duration crop at the same location on a deeper soil as opposed to a short-duration crop on a low water-holding capacity soil. Since soil types and rainfall patterns in the SAT show considerable variations over short distances, such analyses will assist considerably in deriving estimates of crop-growing periods and suitable crops.

By estimating weekly the amounts of available water in the root zone of crops in relation to potential evapotranspiration demand, the probabilities of water availability at pre-determined levels can be determined for a particular soil type. Since the ET rates of crops in relation to the potential evapotranspiration rates are well defined under adequate moisture conditions, a comparison of these to soil-moisture availability estimates should give a better appreciation of the "likely" fitting of crops in a given soil-rainfall-evaporation complex. Figure 9 depicts such an exercise for Hyderabad cbnditions in typical soils and for short-, medium-, and long-duration crops. It is apparent that a long-duration crop in a soil with 50 mm available water-storage capacity will be exposed to soil-moisture inadequacy at several growth stages, but on the other hand if the soil-moisture storage capacity were 150 or 300 mm, the risks of water deficiency are much less. Thus one might select for shallow soils a drought-hardy crop (e.g., castor bean, *Ricinus communis),* whereas in deeper or heavier soils a crop with medium sensitivity to drought (such

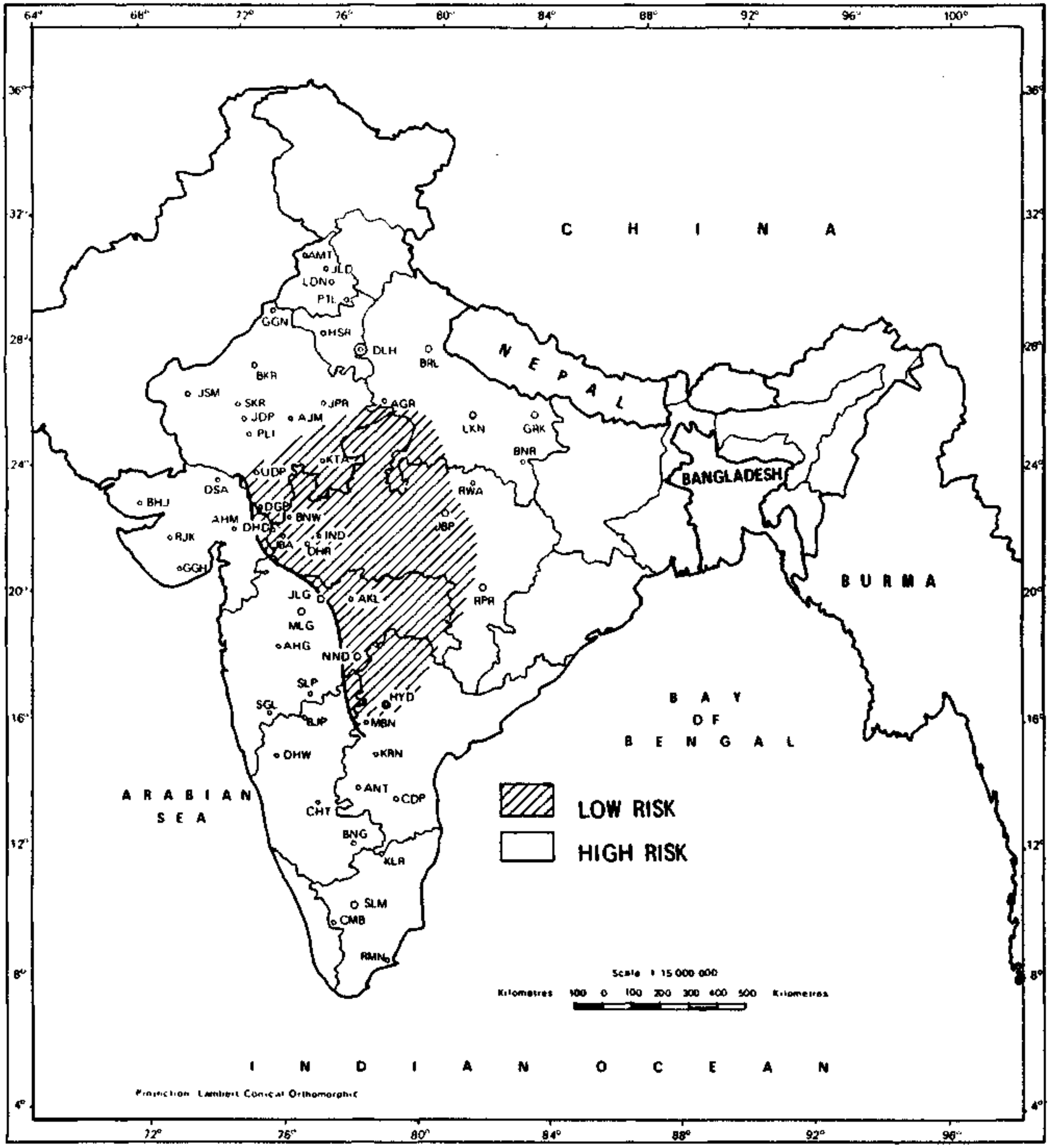


Figure 7. Possibilities of dry seeding on Vertisols.

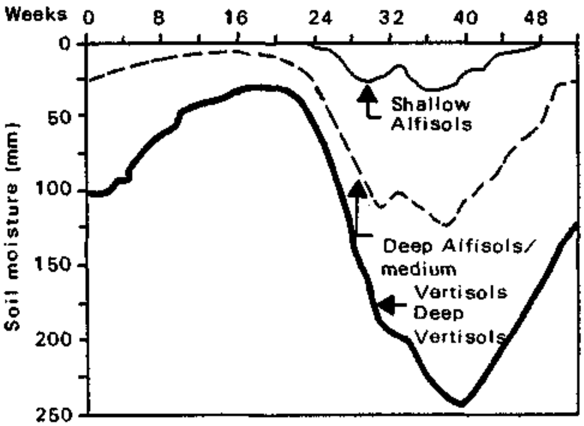


Figure 8. Weekly soil-moisture storage in three soils (Hyderabad, 1901-1970).

as *pigeonpea, Cajanus cajan)* would be suitable. Similarly one could fit in short- and medium-duration crops. Effects of changes in seeding dates and the influence of different phenological characteristics on crop performance could also be assessed as first approximation in such analyses.

Field work-day probabilities at harvest time can be estimated from rainfall probabilities. These probabilities have been computed for millet *(Pennisetum americanum)* and sorghum *(Sorghum bicolor)* crops of different durations (Table 5). The importance of such field work-day probabilites in relation to the harvest of sorghum in two soil types in shown in this table. Farmers in this area grow a long-duration sorghum crop of 130 to 150 days duration. There is a high degree of probability for having at least 3 consecutive work days in either the Alfisols or the Vertisols at harvest time of a long-duration sorghum. Hence there would be no difficulty in harvesting this crop. On the other hand, if one is growing a 90- to 100-day sorghum crop, the possibility of getting into the field for harvest is about 77% in the Alfisols and 29% in the Vertisols. It is fairly common to have intense rain storms (of at least 60 to 70 mm) in this area in the month of August and September. In the deep Vertisol areas, harvesting a medium-duration sorghum could be a problem. Since the sorghum crop is affected with grain mold and also grain rot during wet weather, 90- to 100-day cultivars of sorghum are not likely to be successful in the Hyderabad Vertisol region unless the crop is grain mold/rot resistant. The analysis of field work day probabilities shows that it is not only important to grow a good crop but it is also important to harvest the crop at the opportune time.

Table 5. Field-work day probabilities at harvest of sorghum and millet crops at Hyderabad.

		3 Consecutive work day probability	
Crop	Duration	Alfisols (%)	Vertisols (%)
Millet	65-70	50	4
Sorghum	90-100	77	29
Sorghum	130-150	93	83

Future Research in Agroclimatology

This discussion has so far concentrated on two areas of agroclimatological research: (a) characteristics of the SAT environment, and (b)

Table 4. Length of the growing season[a] for three soil conditions[b]

	Available water-storage capacity		
	Low (50 mm)	Medium (150 mm)	High (300 mm)
Probability	Weeks	Weeks	Weeks
Mean	18	21	26
75%	15	19	23
25%	20	24	30

a. From seed-germinating rains (25 Jun) to end of season (time when profile moisture reduces EA/PE to 0.5).
b. Low: shallow Alfisol; medium: shallow to medium-deep Vertlsols; high: deep Vertlsols.

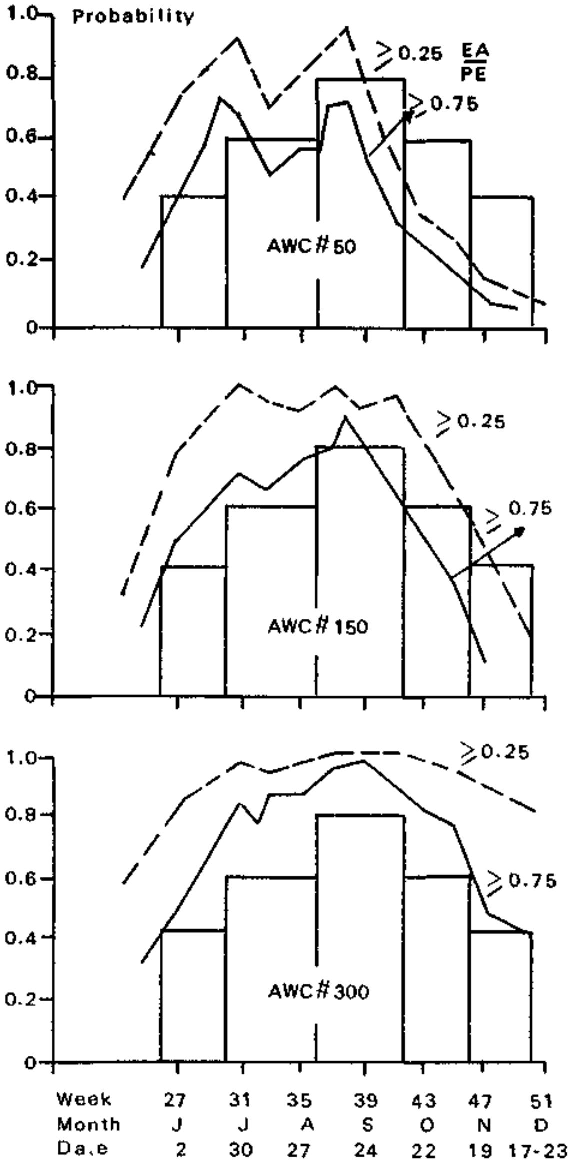
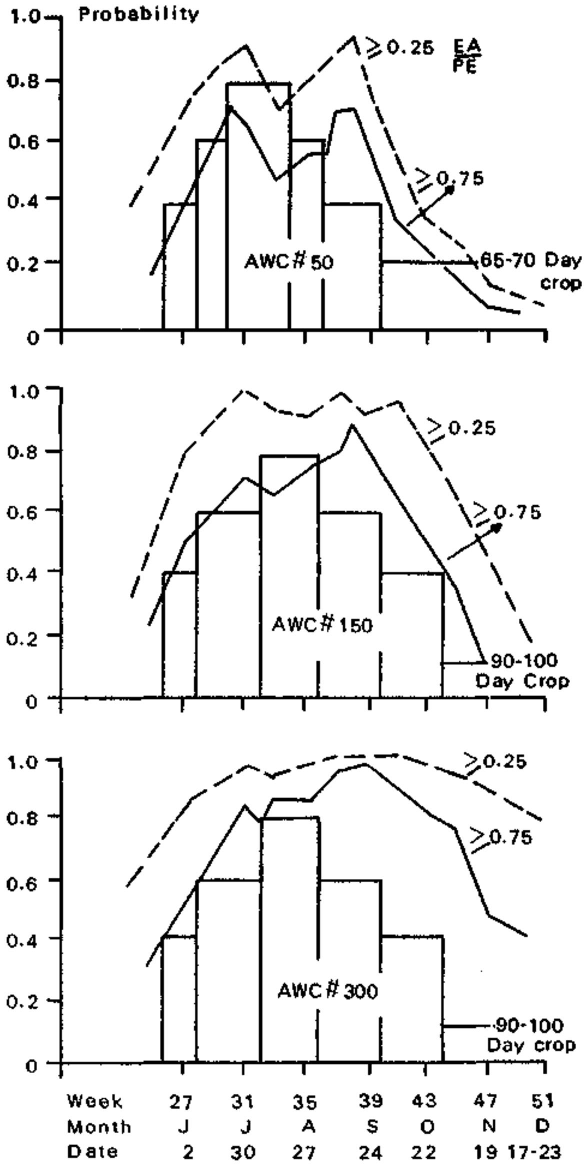


Figure 9a. Fitting of a long-duration crop in three soils.



b. Fitting of short - (65 to 70 days) and medium - (90 to 100 days) duration crops in three soils.

collection of meteorological data at ICRISAT Center and at cooperative research stations, and its interpretation in terms of agronomic relevance. These studies are conducted in collaboration with the Crop Improvement and Economics Research programs at ICRISAT.

Other areas of interest are the microclimatological and crop phenological studies and the crop-weather-modeling studies. These two areas of research are done in collaboration with the Environmental Physics, Crop Physiology, Economics, Hydrology, and the Cropping Systems subprograms. We initiated a microclimatological studies program in 1977, and have been able to acquire a good deal of instrumentation that is needed in these studies. We have been conducting energy-balance studies in different crop canopies in collaboration with the Crop Physiology and Environmental Physics subprograms. These studies are useful to delineate differences in the water-use efficiencies of different crops. We have also three lysimeters in operation, two of them are installed in the deep Vertisol area and one in the Alfisols. Our results in relating the water-use efficiencies of crops to the crop growth are quite interesting. For example, in sole maize *(Zea mays)* we found that changes in the actual water use to the potential water use (ET/Ep) are fairly well related to the leaf-area index of the crop. This finding has important implications for our efforts to model the actual water use of different crops. Our preliminary work has showed that the relationship between ET/Ep and leaf-area index is also true in a maize/pigeonpea intercrop.

To summarize, in pursuing our objectives for the next 5 years, we hope:

1. To develop an understanding of rainfall variability across diverse locations for quantifying associated risks in crop production.
2. To characterize crop response to prevailing moisture environment, to assist in crop planning for increased and stabilized agricultural production.
3. To develop a climate-driven crop-production model based upon crop-weather interaction studies, to predict crop performance under different locations.
4. To develop agronomically relevant classification of the climate for identifying isoclimes for assisting the transfer of technology.

Our emphasis on the studies on rainfall probabilities is likely to continue over the next 2 years so that we can characterize the climatic environment of the different areas in which we are interested. We also believe that studies on water balance (which give us the soil moisture probabilities) will be continuing upto 1980. This work will be done in collaboration with the Environmental Physics and the Hydrology subprograms. Crop-weather modelling, an area of research that will receive considerable attention in the next 5 years, is now under way. From these studies, we plan to work out crop-yield probabilities, using the climate-driven models that would be developed in the next few years.

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Agrometeorological Network over Africa: Collection, Documentation, and Analysis of Data

D. Rijks*

Summary

The organization of an effective agrometeorological service is a long-range program. Its positive influence on agricultural production is beyond question, as experience in countries elsewhere in the world has shown.

The basis of its success is the collection of accurate and representative observations that can be effectively and rapidly transmitted, analyzed, interpreted, and used.

The impact of the information provided by these services may not become felt for several years after the start of the program; all the more reason, therefore, to start the first phases of its implementation without delay.

An agrometeorological service is a service that provides information on meteorological conditions and plant and animal growth characteristics that affect agricultural production in the widest sense. A fully operational service assures the making, transmission, verification, and analysis of observations, their useful storage, and the formulation and dissemination of information that may increase agricultural production or reduce the effect of factors that hinder optimal production.

Semi-arid conditions prevail, for most of the growing season of rain-grown crops, in the so-called semi-arid regions of Africa, the Sahel and the Botswana area. Semi-arid conditions can also be encountered at the beginning and the end of each of the rainy seasons in equatorial areas with a bimodal rainfall pattern, even if total annual rainfall in such areas may be well in excess of 1000 mm per year. Such areas exist notably in Kenya and Tanzania.

To be fully effective, an agrometeorological service needs ,an operational network, a documentation analysis center, and an information-dissemination service. This paper describes a system that is being developed by the eight countries of the Sahel area in the context of the cooperation established by the Permanent Interstate Commission on Drought Control (CILSS).

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Collection of Data

Steps in the establishment of operation of an agrometeorological network are:

- Definition of a methodology
- Observer training
- Installation of stations — site selection, choice of instruments, and selection of observations to be made
- Recording procedures for observations
- Transmission of observations
- Verification of observations
- Maintenance operations

Methodology

The Sahel countries cooperating in the CILSS Agrhymet program cover an area of about 4000 km in an east-west direction and about 1000 km in the north-south direction. During the rainy season, from about June to October, the movement of rainfall zones is from east to west. Weather conditions in the east may therefore significantly affect production in westerly areas. A common methodology throughout the area facilitates the interpretation of "upwind" observations and results for use "downwind," and the application of results of research obtained elsewhere.

A common methodology has therefore been developed by agrometeorologists from all the countries involved. This methodology is founded on basic concepts and guidelines formulated by WMO and by the FAO/WMO interagency group on agrometeorology. It is being developed and detailed by twice-yearly meetings of the agrometeorologists of the Sahel countries. Preliminary publication of parts of this methodology, in loose-leaf binders, permits staff in the countries concerned to accumulate working experience with these documents; revisions and additions will be issued when necessary. A short, summary-like version of this methodology will be provided to observers, as an Observers' Handbook.

Observer Training

In the past, agrometeorological observations were generally made by meteorological observers who were taught, usually during on-the-job training, to observe the phenology of crops, soil-water status, and agricultural conditions. Many of these observers were employed at agricultural research stations, where they worked under the supervision of agronomists. Very few observations were made on the growth of natural vegetation, pasture, and condition of the livestock. Observations on insect attacks were made by specialized teams. Meteorological and agricultural services in the Sahel countries now realize that a more full use could be made of staff in each of these services, if suitable training were provided. In the context of the Agrhymet program and the crop-protection projects of CILSS, observer training will therefore from now on be oriented towards the training of muitidisciplinary observers. The meteorological component of the program will involve only ground observations. Further components are soil-water observations, crop phenology and agricultural operations, and observations of insects and diseases. This training can be given either at national agricultural or meteorological training centers. The syllabus will be prepared by a team of CILSS/WMO/FAO instructors at the Niamey Agrhymet Center. Instruction will be given by instructors temporarily assigned forthis purpose from national meteorological and agricultural services, assisted by two roving instructors at the Agrhymet Center. Total training will last about 9 months. Training courses will start with meteorological and "theoretical" components in the dry season and be concluded with practical training during the rainy season. Training is scheduled to start in February 1979. Candidates for training should have the junior high school leaving-certificate (BEPC) or equivalent in-service experience.

Installation of Stations

The selection of sites for stations is based on the economic importance of the agriculture in a region, and on the availability of other meteorological stations in the area. Sites at agricultural experiment stations are obviously desirable, but must be complemented by other sites in different ecological zones or in areas where the agricultural-production pattern is different. Maximum use is made of locations with existing climatological stations, so that interpretation of observations in any one year can be made in the light of long-term weather observations.

The immediate aim is to establish between four and ten stations per country. The long-term goal is to have a station in each major agricultural-productionzone; insomecountries this could mean perhaps as many as 15 to 20 stations.

The usual range of meteorological instruments includes raingauge, recording raingauge, screen with wet and dry maximum and minimum thermometers, thermographs, hygrograph, run-of-wind anemometer at the 2-m height, wind-direction indicator, soil thermometers, sunshine recorder, and a Class-A evaporation pan.

Solar radiation is recorded at about 40 stations in the Sahel area. Soil-water observations are made visually and by use of Bouyoucos blocks. Experience with the latter technique shows that a quantitative assessment of soil water is often difficult. The blocks, however, do give a good indication about the progress of a wetting or drying front. At some stations, observations are made using the Wallingford neutron probe. At all stations the results of the above three methods are regularly compared with observations obtained by gravimetric sampling.

The depth of observations varies according to the technique used. Visual observations are made at the surface and down to 0.2 m; Bouyoucos blocks are installed at the 0.1-, 0.2-, 0.5-, and 1-m levels. Gravimetric sampling is by 0.2-m depth intervals down to 1.2 m or more, according to root depth. Neutron-probe observations normally go down to 2.4 m.

For plant observations no instruments other than ruler and balance are used at present. The observations vary somewhat from crop to crop. They include the dates of specific stages of development of the crop — numbers of plants, leaves, flowers, or branches. Length of stems, leaves, and other dimensions of vegetative or generative parts of plants are recorded. They also include crop observations, such as incidence of weeds, insect attacks, or diseases, along with adverse meteorological phenomena, such as hail, drought, or lightning. A further type of observation details the factors thatdetermineyield: number of plants, number offruitsperfruiting body, percentage of full and empty fruits, weight per fruit, etc. At the end of the season, yield is recorded.

Recording Procedures

A register for crop observations has been designed and will be used for several years, after which it may, if necessary, be modified in the light of the experience obtained before being adopted. This register provides space for a number of different crops that may not all be grown at any one station. Meteorological observations are being recorded on forms provided by the Meteorological Services of the area. A modified layout, permitting easy transfer onto computer media, is under study. This modified layout was originally adapted to recording on 80-column cards, but the advent of key board/display screen minicomputers may make a more flexible recording procedure possible.

A special WMO code, the Agmet code, has been developed to permit easy and rapid transmission of messages. This code consists of three designatorgroups, nine meteorological groups, and an unlimited number of crop groups. Each group consists of five digits.

Transmission of Observations

The aim of the Agrhymet program is to equip each key agrometeorological station with HF voice transmission equipment (SSB) so that daily contact can be made with national headquarters. This transmission is similar to that practiced at present by synoptic stations. It will be effected once daily, probably between 0900 and 1100 hrs using the codes described above. Upon receipt at national headquarters the message will be entered on a minicomputer, verified and available on the one hand for inclusion in the national archives (on tape or disc) and on the other hand for transmission by radio teletype to the Niamey Regional Agrhymet Centre. From about midday onwards this message will therefore be available for analysis both at national and regional headquarters.

Verification of Observations

Verification of observations received at national headquarters will be effected by a check for internal consistency of the message once recorded on the minicomputer, by a check against a norms file, and, if the system can be adequately developed, by a geographical check. Observers at stations will be on standby at a certain hour during the morning to reply to possible questions, and to repeat information, if required. The precise definition of the criteria for verification will evolve over a period of years, taking into account the experience acquired.

Maintenance

No operational service can exist without the provision for maintenance. The institution of maintenance capabilities must accompany the installation of instruments and equipment. Maintenance technicians will be trained in the context of the Agrhymet program as of February 1979. The duration of the course will be 2 years. Candidates must possess a senior secondary school certificate (Bac C or D or technique). The course covers all meteorological and hydrological instruments and the telecommunications equipment. Maintenance laboratories will be located in each capital. Mobile maintenance units may be established at a later date.

Documentation and Analysis

Data files will be established at national and regional headquarters as from the beginning of the operational phase of the program. Acquisition of past meteorological observations in digital form for these centers is undertaken with the cooperation of ASECNA, ORSTOM, and a Belgian contribution to the program. Acquisition of past agricultural and phenological observations may be more difficult, but should be attempted with the help of government departments and research institutions.

Analysis can be undertaken at national headquarters within the limits imposed by available computer capacity, scientific expertise, and data banks. The facilities of the regional center may be used for analysis that requires a regional rather than a national volume of data, special scientific knowledge that may not be available at any one moment at national headquarters, or an enlarged computer capacity. The quasi-real-time analysis of data collected by 1200 should be achieved by 1800 or 1900 hours each day.

It is considered that certain routine analyses should be executed daily by the regional center, using data that have been transmitted by 1200 hrs. This analysis could cover water balance calculations, and information on planting and early development of crops, on disease and pest incidence and potential pest and disease development, on harvesting conditions, etc. At a later date, information on irrigation requirements may be formulated. Other fields of application could concern temperature regimes, as for instance forthe February sowing of irrigated rice. The hydrological component of the program could provide rapid information for the practice of flood retreat crops. Many other applications may become practical.

Accumulated data banks will also allow easy access for statistical analyses that are needed by the planification services. At present, meteorological and hydrological aspects in rural development planning are often insufficiently researched because establishing an access to accumulated data is too time consuming.

Dissemination of Information

The dissemination process depends on the nature of the information that was requested or provided and on the users to be contacted.

Summaries of statistical analysis of past data often are specifically requested for planning purposes by well-defined users and can be transmitted directly to them. It can also be disseminated in print, restricted, or as a general publication.

Information derived from analysis of quasi-real-time data can be considered to have two distinct groups of users numbering in the tens or hundreds per country, one consists of planners and persons charged with the execution of specific programs or activities, e.g. crop production. The other group, numbering in the millions, consists of the primary producers in the Sahel, the farmers and herdsmen.

Data assembled by the end of each day at national headquarters, either from its own sources, or after retransmission by radio teletype from the Niamey regional center can be multiplied by electronic stencil and distributed to the officials concerned. In this way, observations from field stations made by 0800 hrs on a certain day should result in consolidated information available at the government officials' desk the next morning at 0800 hrs.

To reach the primary producers, radio broadcasts are the best mode of diffusion. Appropriate information should be given at the end of the day to a small group of people especially qualified to put it in a form that can be easily understood by farmers and herdsmen. This group might consist of a hydrometeorologist, an agronomist, an agricultural extension specialist, a radio broadcast specialist, and a rural sociologist.

It is essential that the agricultural departments and the agricultural extension services participate fully in these dissemination activities. Agricultural extension workers in the villages should be adequately trained in the interpretation and explanation of such messages at the village level.

Effective methods for disseminating information need to be more fully studied, with the active cooperation of social scientists and officials of agricultural departments, and the results of such a study must be carefully examined before implementation.

Role of the Regional Agrhymet Center

The regional agrhymet center has three main areas of activity:

- Training;
- Data analysis and information dissemination; and
- Applied research

It cooperates, wherever possible, with institutions with similar objectives in Africa and elsewhere in the world.

Training

The training of Class IV personnel (observers) is assured by the national meteorological services. The Center, however, provides the syllabus and teaching materials. It may also, on request, provide instructors in specialized fields, such as phenological observations, or simple instrument maintenance, or coding and transmission of messages. It can sanction such training by issuing a diploma, after successful completion of an examination.

The training of Class III personnel in agrometeorological or hydrological techniques has been, and will continue to be, a major activity of the center. Candidates with Senior High School Leaving Certificate can be admitted as well as candidates at an equivalent level who have passed a series of competitive tests. The training program has been established according to WMO guidelines and extends over 2 years, including practical work. Seventy students have so far (until 1978) been accepted by the center, of whom 30 have received their diploma. Several other Francophone African states have asked admission to the center for students from their countries.

One training course has been held for Class II personnel in agrometeorology. A second 2-year course will start in late 1978; candidates must have 2 years of university training in mathematics, physics, meteorology, agriculture, or biology. The program follows the WMO guidelines.

No training of Class I personnel in agrometeorology or hydrology has so far been undertaken. It has been considered that the resources available at the center should, in the first instance, be directed to the training of a large number of technicians rather than of a small number of Class I personnel.

Data Analysis

Data analysis will concern three major fields of activity:

- Analysis of data in real-time or quasi-real-time for operational purposes;
- Analysis of past data;
- Analysis to provide ground-truth data for satellite imagery interpretation.

Analysis in (Quasi) Real-Time

This analysis will be effected for use by executives of operational (government) services and primary producers. It will cover water-balance analysis on a day-to-day basis, taking into account the crop, soil, and weather characteristics; conditions for sowing; growth and availability of natural pasture; conditions for harvesting; existing and probable outbreaks of pests and diseases; irrigation requirements; temperature requirements for irrigated dry season crops. It may also, in cooperation with the agricultural services, give details on agricultural operations, such as fertilizer application, that are conditioned by meteorological conditions that affect crops.

Analysis of Past Data

This analysis will cover a wide field of subjects, which can be added to as needed. Analysis of past rainfall data, already well under way, will becompleted, including probabilities at different levels and time scales, intensity analysis, and calculation of erosion hazard.

Water-balance calculations will form a major part of the analysis. We feel that the time of water-balance calculations based on mean values of rainfall and evaporation has passed and that the variability in available water under specified conditions and based on a run of individual data of rainfall and evaporation of past years is now required. Such analysis will aid in the selection of crops and varieties, sowing dates, and agricultural practices, including irrigation.

An analysis will also be made of temperature regimes in areas with a dry-season (cool or hot) irrigation potential, to assist in a rational choice of crops, varieties, and agricultural practices.

Analysis of wind data will be made to assess the potential of exploitation of eolian energy.

The analysis of data to provide ground truth for Landsat imagery interpretation will have to be defined in detail after consultation with the Ouagadougou Center for telemonitoring and the various users, such as FAO, CILSS, and many overseas universities. Conversely, Landsat imagery will be of great value in the preparation of information in quasi-real-time.

The data analysis operations will start after installation of the necessary equipment, foreseen for autumn 1979. This part of the program should be operational by 1982.

Applied Research

The Center will have a role in the execution of applied research in cooperation and association with other national and international organizations and government departments. This applied research may cover, among other subjects, plant-soil-atmosphere relationships in different crops and under different agricultural conditions; the energy balance over different surfaces; the radiation balance; the effect of extreme temperatures on agricultural production; the wind regime and its exploitation; the economic use of water in agriculture; grain storage at the village level; and erosion control. Other subjects may well become priority items of research by the time this aspect of the Center's activity becomes fully operational, which is probably not before 1985.

Climatological Features of the Semi-Arid Tropics: Meteorological Network and Studies in Northeast Brazil

Antonio C. S. Reis*

Summary

Northeast Brazil is a semi-arid area with a well established network of meteorological stations. Thereare 103 main climatological stations for collection of routine meteorological observations. Most of the surface data collected by several organizations from these stations have been computerized and stored on magnetic tapes. In addition, upper-air data are also collected routinely by five different organizations. A recent survey identified seven centers in the northeast Brazil which are starting or already carrying out agrometeorological data collection in northeast Brazil is characterized by duplication and needs new and uptodate equipment and trained personnel. Procedures for standardization and centralization of data processing are urgently required.

Northeast Brazil occupies an area of about 1.5 million square kilometers[1] of which approximately 700 000 to 800 000 km[2] are within the area usually known as the "Drought Pologon" (Poligono das Secas); the area has a semi-arid climate. This region is located between 2° ana 17°S and 34° and 47°W. It has according to the official estimates for 1978[2] a population of 34 500 000 inhabitants, almost 30% of Brazil's total. The area is strongly affected by periodic drought, which often depends more on social and economic conditions than on meteorological factors. This fact can be clearly demonstrated by comparing the annual rainfall chart (Fig. 1) and the percentage of drought incidence (Fig. 2).

Systematic weather observations in Northeast Brazil started in 1909withtheinstallationof a network of pluviometric and hydrometric stations located in the main river basins of the region. During many decades, this network was established and managed by the Departmento Nacional de Obras Contra as Secas, or DNOCS (National Department of Works Against the Drought). The pluviometric data obtained from a network of 352 DNOCS stations are published on a monthly basis.[3] They are available, on a daily basis, in the Superintendencia do Desenvolvimento do Nordeste, or SUDENE (Northeast Development Superintendence) at its Departmento de Recursos Naturais, DRN (Natural Resources Department). SUDENE[4] also published the "in natura" data of 725 pluviometric stations, on a monthly basis, using information obtained from the DNOCS network, filled out with data obtained elsewhere.

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Meteorological Network of Northeast Brazil

In Brazil, meteorological observations, data collecting, processing and analysis; and weather forecasting are performed by the Instituto Nacional de Meteorologia (INEMET), Ministerio da Agricultura (National Meteorological Institute, Agricultural Ministry). This Institute has maintained 42 surface meteorological stations,

1. From Empresa Pernambucana de Pesquisa Agropecuaria, IPA, Recife, Pernambuco, Brasil.
2. "Anuario Estatistico do Brasil," 1976 — IBGE, v. 37, Rio de Janeiro, Brasil.
3. Observacoes Pluviometricas do Nordeste do Brasil, 1969, DNOCS, Fortaleza, Ceara, Brasil.
4. Dados Pluviometricos Mensais *in natura,* 1970. SUDENE-DRN, Recife, Pernambuco, Brasil.

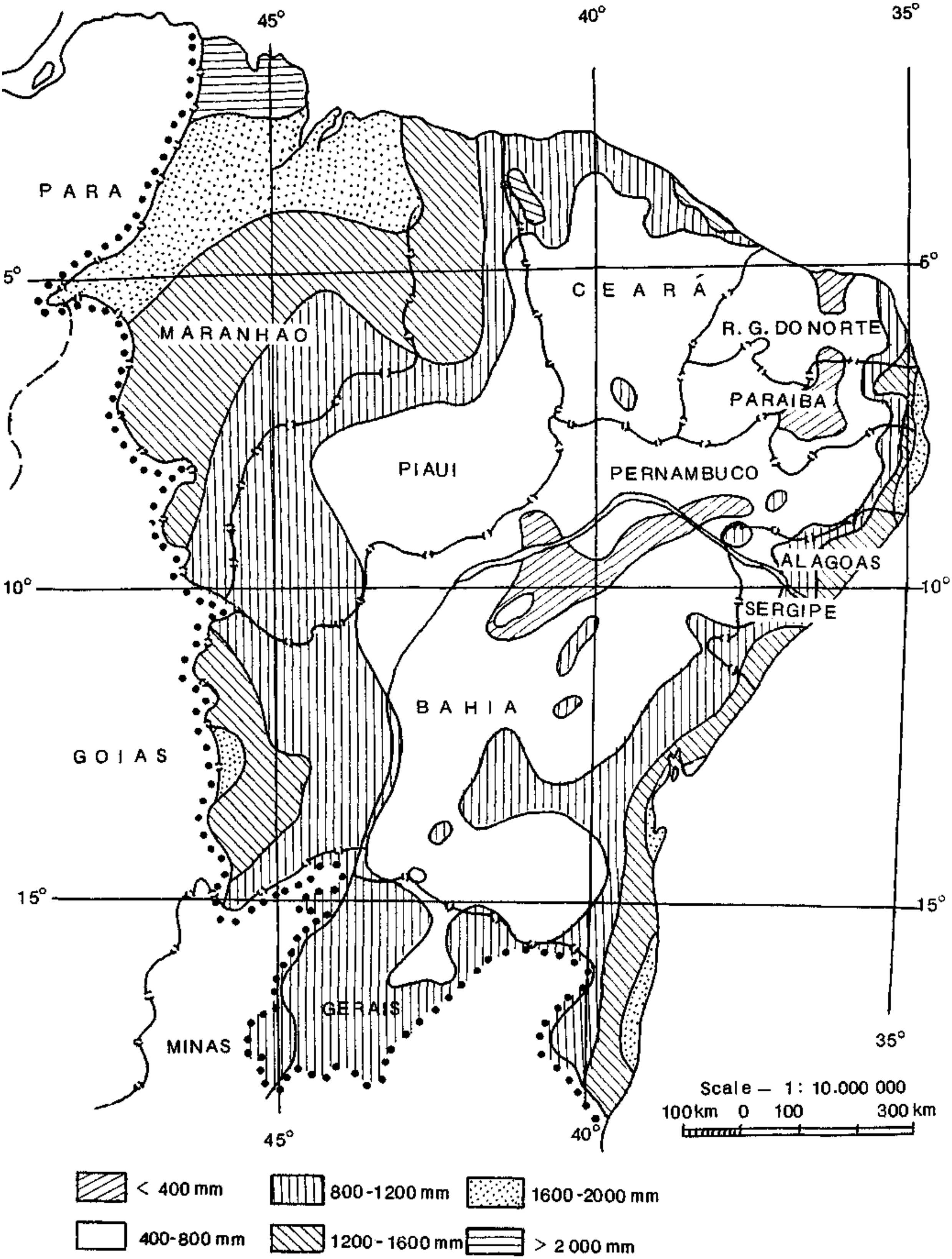

Figure 1. Annual mean rainfall in Northeast Brazil.

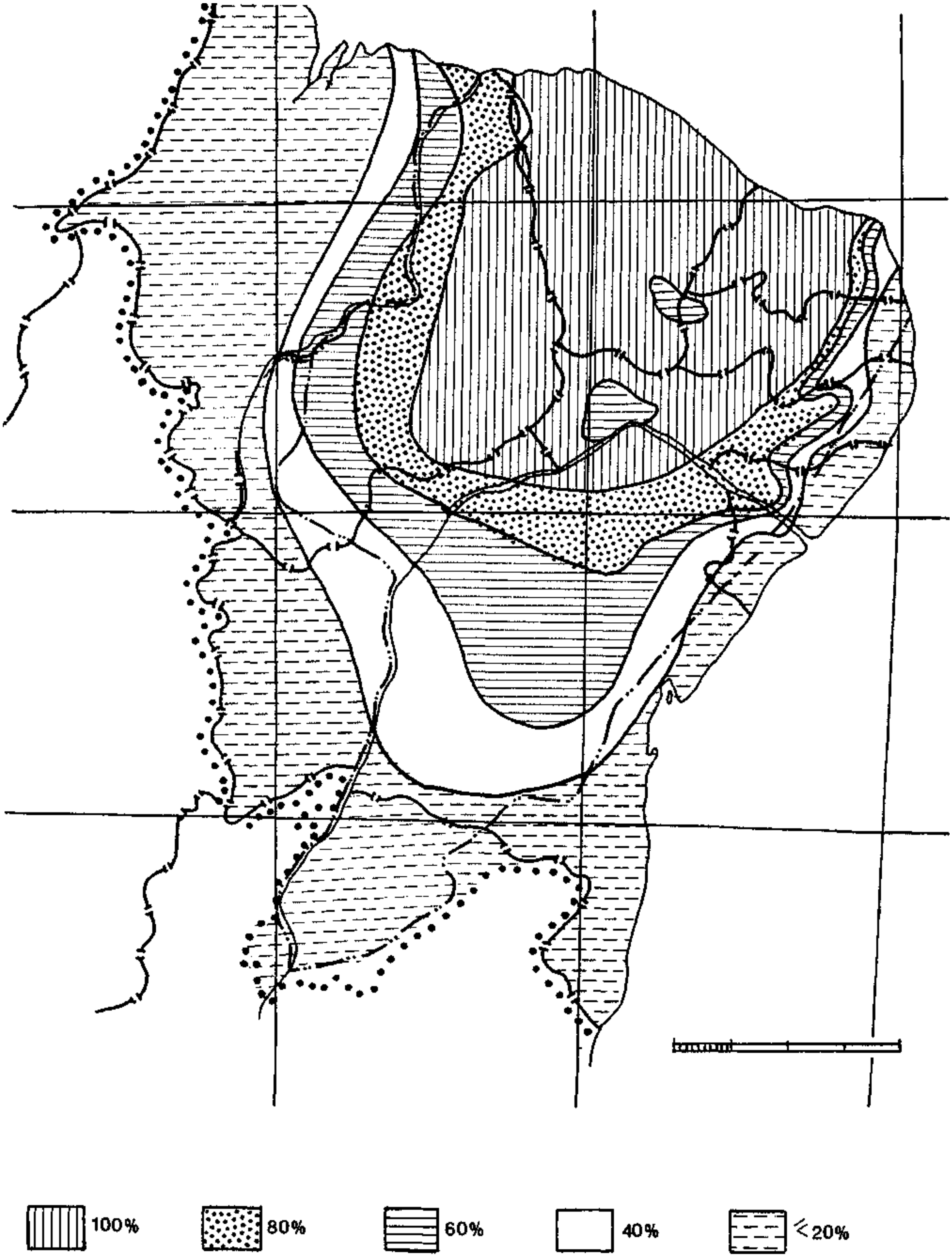

Figure 2. Drought incidence (%) in Northeast Brazil

classified as "main climatological stations (synoptic)," in Northeast, since 1960.

When SUDENE was established it became concerned with the installation of meteorological networks that could provide the basic information necessary for the region. SUDENE carried out studies related to the distribution of stations geographically, the selection and training of meteorological station personnel; as well as the installation and maintenance of the network during its first years of functioning. Agreements for technical and financial cooperation were signed between SUDENE, INEMET, and international organizations such as the WMO.

From the previous INEMET network, 38 stations were utilized after being almost entirely re-equipped and rebuilt.

All the stations of the Northeast network were set up according to the predetermined pattern and equipped with standard set of instruments.

Twenty-two aerological stations (10 radiosonde and 12 pilot balloon) and 103 surface stations (main climatological) are now in operation in Northeast Brazil (Fig. 3).

In regard to the pluviometric network, SUDENE has increased to more than 2000 the number of pluviometers inthis region (Fig. 4,5).

The number of meteorological stations in operation in the Northeast and the number of pluviometers and evaporimeters (Class A-Pan) are summarized in Table 1. Figures 6 and 7 show the geographical distribution of the pluviographs and evaporimeters, respectively.

Routine Observations

Observations carried out in the 103 main climatological stations include:

- Atmospheric pressure
- Barometric tendency
- Surface-air temperature
- Maximum and minimum temperatures
- Humidity
- Rainfall (including intensity and duration)
- Evaporation
- Direction and speed of the surface wind
- Soil temperature at different depths
- Duration of bright sunshine
- Total incoming radiation (direct plus diffuse)

Daily surface observations are made at 0900 (12 GMT), 1500 (18 GMT), and at 2100 (24 GMT) hours. Aerological probings are made only at 0900 (12 GMT) hours.

Instrumentation

Atmospheric pressure is observed through mercury barometers (Fortin-type or Kew-type) and aneroid microbarographs.

The observations of the surface-air temperature utilize a standard thermometer (liquid-in-glass) and the humidity is observed through aspirated air psychrometers (August type). Each station is still equipped with a weekly recording thermohygrograph. Instrument shelters are set at 1.5 to 1.8 m above the ground.

Table 1. Meteorological Network, Northeast Brazil, 1978.

State	Climatological Stations	Aerological Stations		Pluvio-meters	Pluvio-graphs	Evaporimeters Class-A Pan
		Radiosonde	Pilot Balloon			
Maranhao	13	2	1	113	6	1
Piaui	12	1	3	202	15	9
Ceara	12	1	2	257	34	16
Rio G. do Norte	5	-	-	131	13	5
Paraiba	7	-	1	134	14	5
Pernambuco	10	2	-	275	25	9
Alagoas	6	-	-	65	1	1
Sergipe	3	-	1	62	3	3
Bahia	28	3	3	564	37	8
Minas Gerais	6	-	1	102	2	-
Fernando de Noronha	1	1	-	1	1	1
Total	103	10	12	2006	151	58

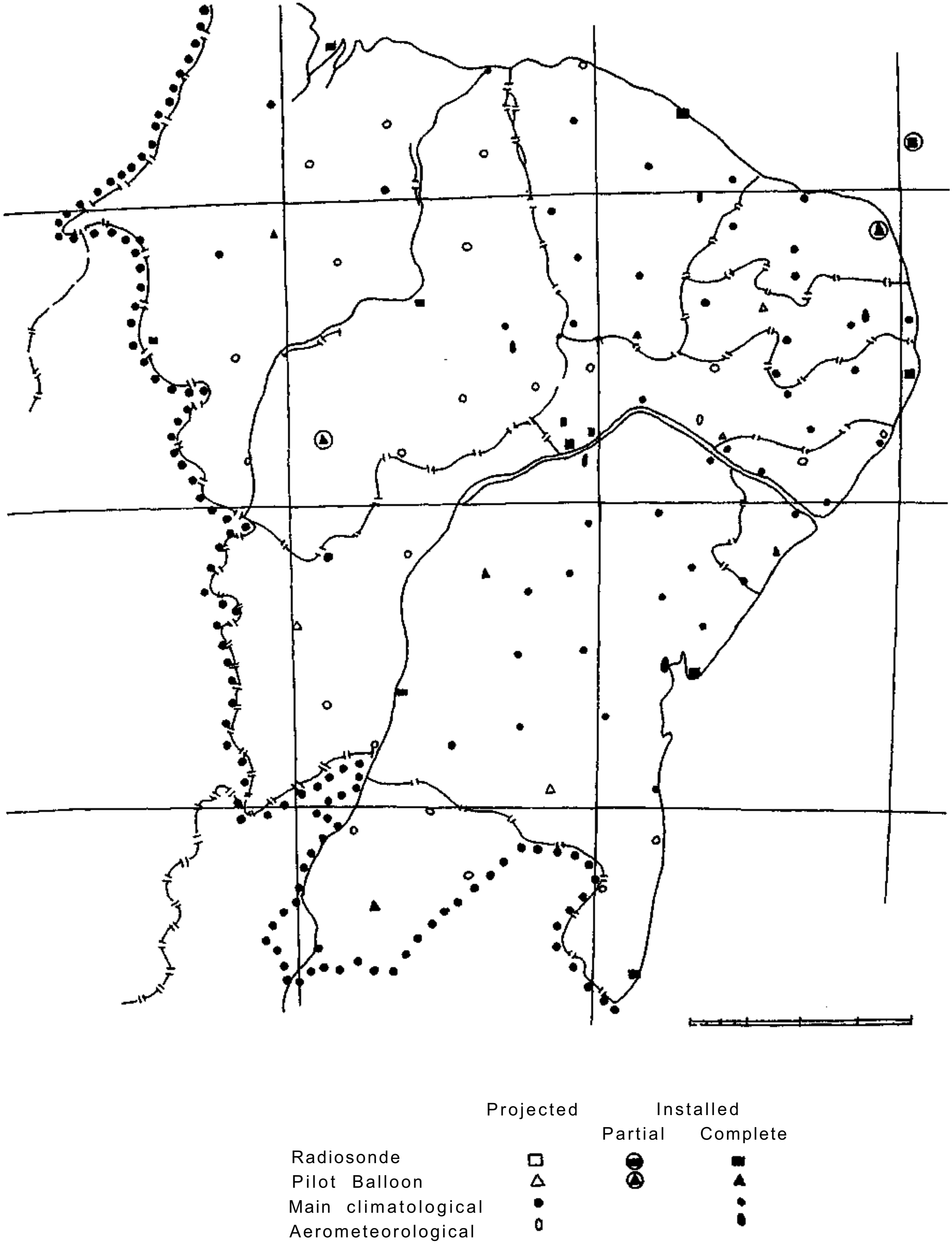

Figure 3. Meteorological network (geographical distribution) in Northeast Brazil.

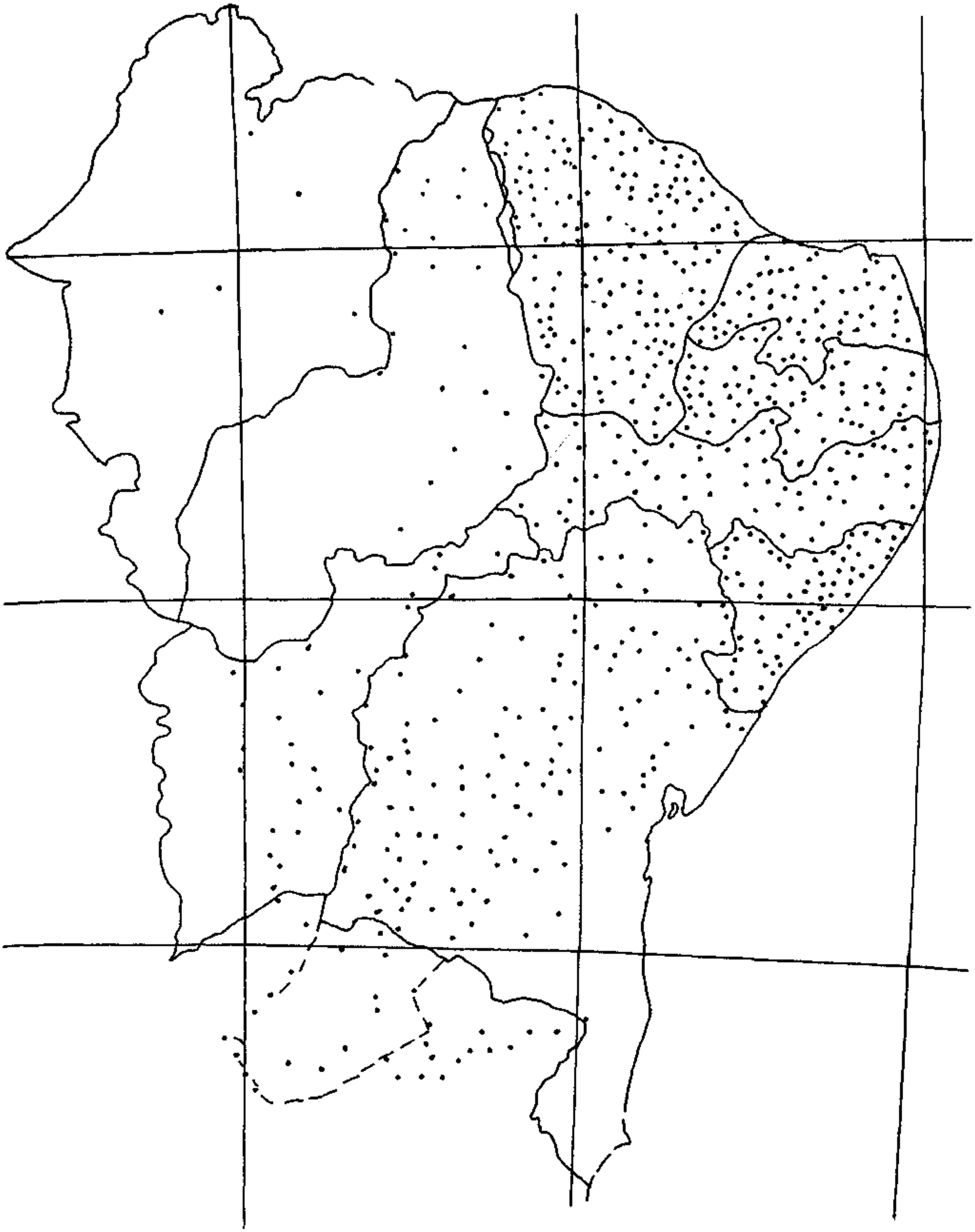

Figure 4. The DNOCS pluviometric network in Northeast Brazil before 1960.

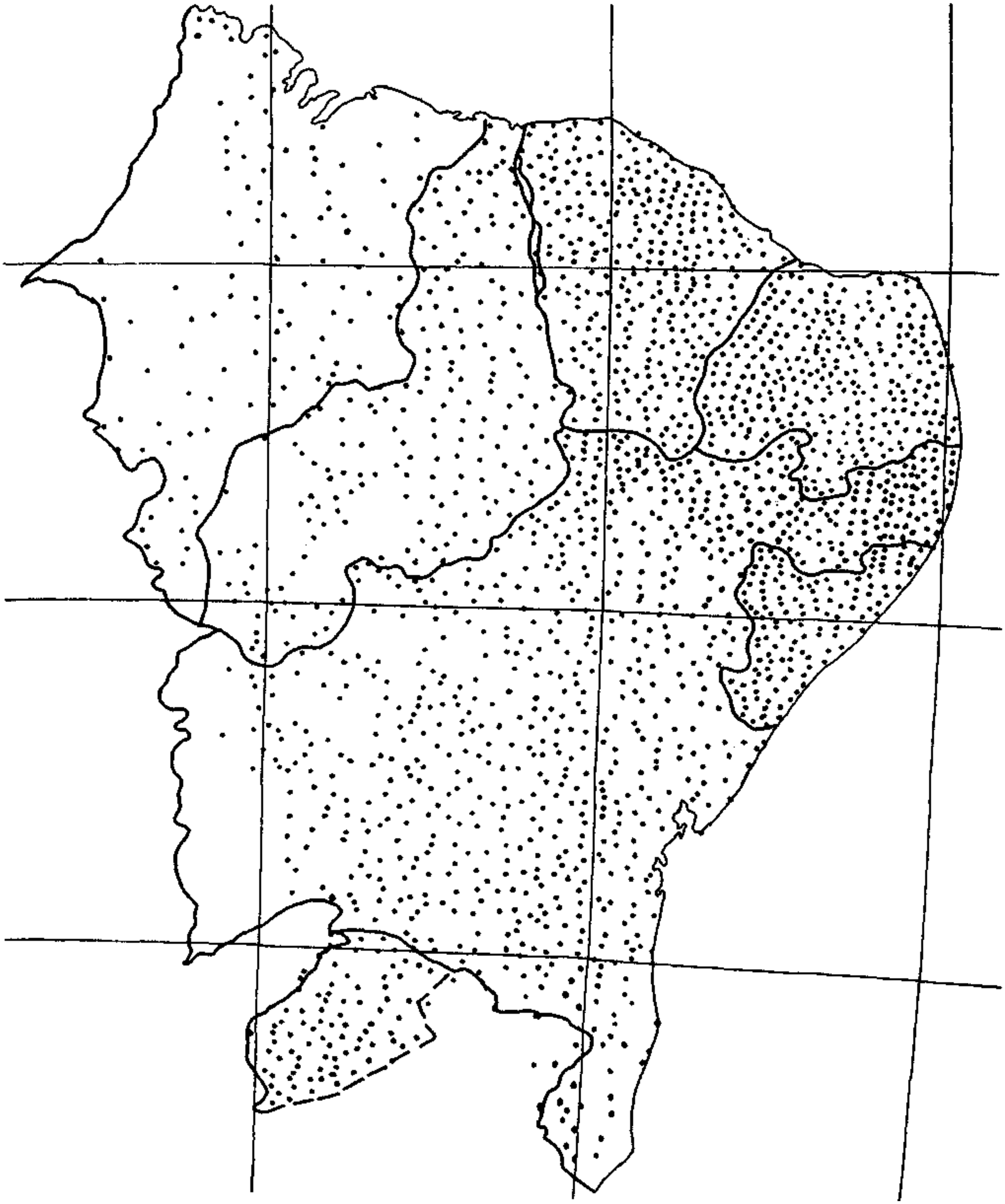

Figure 5. The present distribution of pluviometers in Northeast Brazil.

Rainfall is measured by standard raingauges (Ville de Paris type). The rainfall record is made through syphon pluviographs (Hellmann-type), or by balance and syphon type.

Evaporation is measured by the known "USWB Class A land pan" utilizing a still-well and a micrometer. The so-called Piche evaporimeters are also installed in the shelters.

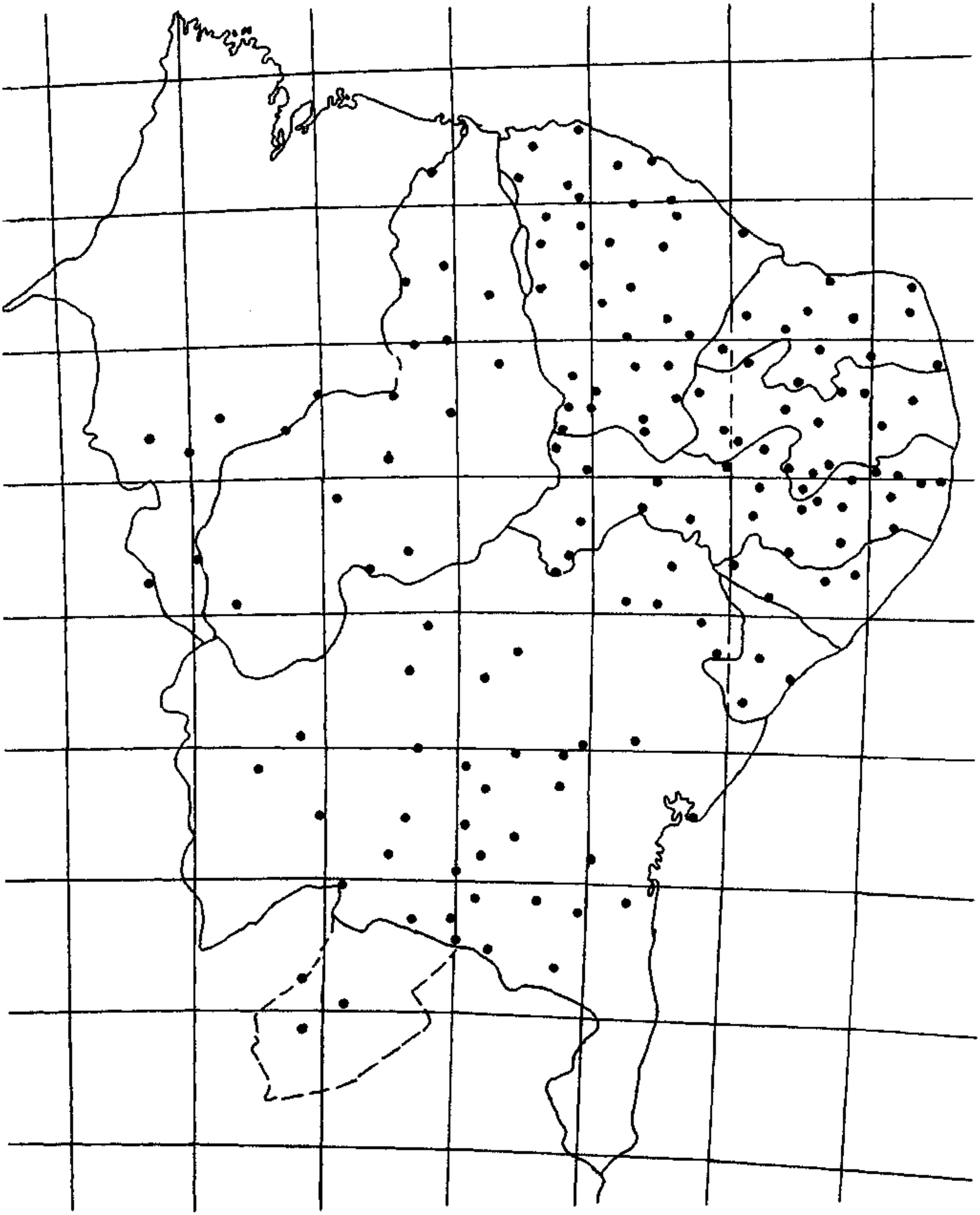

Figure 6. Geographical distribution of pluviographs in Northeast Brazil.

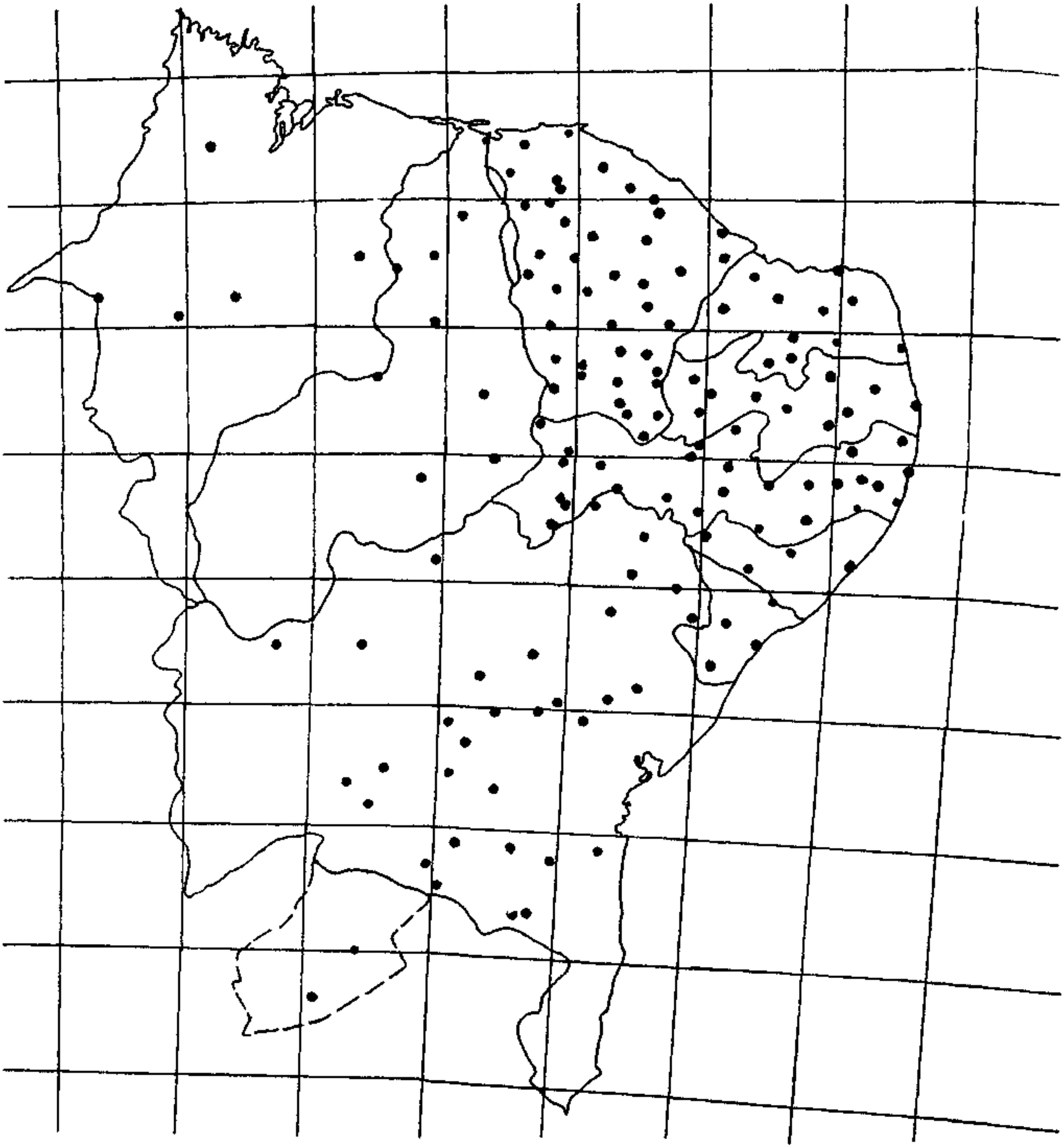

Figure 7. Thermo-evaporimetric network in Northeast Brazil.

Direction and speed of the surface wind are observed through the anemographs (Universal type) located 10 m above the ground. As an additional instrument, the wind vane (Wild type) is utilized. Some stations are equipped with an electric anemometer located 2 m above the ground.

Soil temperatures are obtained through a set of mercury-in-glass geothermometers at different depths, generally at 5, 10, 20, 50, and (in some cases) 100 cm.

The duration of sunshine is obtained through crystal-sphere heliographs (Campbell-Stokes type), and the total incoming radiation is obtained through bimetallic weekly recording actinographs (Robitzsch-type).

The radiosonde stations utilize the equipment "Vaisala", model RS-21. 12, and the radio-theodolite "METOX."

Meteorological Data; the Situation in September 1978

Surface Data

Several organizations, some of which are listed below, collect surface meteorological data in Northeast Brazil. They include:

- Instituto Nacional de Meteorologia (INEMET), Minist6rio da Agricultura (National Meteorological Institute, Ministry of Agriculture);
- Diretoria de Electrdnica e Protecao ao V6o (DEPV), Ministerio da Aeronautica (Electronics and Flying Protection Management, Air Force Ministry);
- Departamento Nacional de Obras Contra as Secas (DNOCS), Minist6rio do Interior (National Department of Works Against the Drought, Interior Ministry);
- Superintendencia do Desenvolvimento do Nordeste (SUDENE), Ministerio do Interior (Northeast Development Superintendence, Interior Ministry);
- Diretoria de Hidrografia e Navegacao — DHN, Ministerio da Marinha(Hydrographic and Navigation Management, Navy Ministry);
- Universidade Federal da Paraiba (UFPb), Minist6rio da Educacao e Cultura (Federal University of the State of *Paraiba,* Education and Welfare Ministry);
- Instituto de Atividades Espaciais, IAE do Centro T6cnico Aeroespacial CTA, "Ministerio da Aeronautica" (Spacial Activities Institute of Technical Aerospacial Center, Air Force Ministry);
- Other institutions such as IPA, Agricultural Colleges, EMBRAPA Research Centers, Agricultural State Secretariats, etc.

The detailed operations and data collected by these agencies are described below.

INEMET

The National Meteorological Institute, under an agreement with SUDENE, operates 103 main climatological stations in the Northeast. Some have been functioning since the beginning of the century. These stations collect about 15 meteorological observations three times per day, and have an average of six or seven recording instruments with daily or weekly charts.

Most of the data of the INEMET climatological stations in the Northeast are computerized and stored on magnetic tape, as follows:

From 1910 to 1960: These data were processed by the "Instituto de Pesquisas Espaciais — INPE" (Space Research Institute), in Sao Jose dos Campos, Sao Paulo, and by the "Associacao Tecnico-Cienti'fica Luiz de Oliveira Junior —ATECEL", "UFPb" (Technical-Scientific Association Luiz de Oliveira Junior), in Campina Grande, Paraiba, utilizing "SUDENE" funds. The magnetic tapes can be found in "SUDENE" headquarters in Recife, Pernambuco.

From 1961 to 1970: These data were processed by the "Instituto de Pesquisas Espaciais — INPE" (Space Research Institute), in Sao Jos6 dos Campos, Sao Paulo, utilizing the funds of this Institute and "INEMET." The data are in magnetic tapes and can be obtained from "INEMET" headquarters, in Brasilia or from "INPE" headquarters in Sao Jose dos Campos, Sao Paulo.

From 1970 on: These data are being processed and can be found at present in "INEMET" headquarters in Brasilia, Distrito Federal. There is no provision as to the conclusion of these activities.

DEPV/IAE-CTA

The "Diretoria de Electrdnica e Protecao ao V6o —DEPV" (Electronics and Flying Protection Management) operates synoptic aeronautical stations in the main airports of the region. Most of these collect about 15 meteorological parameters each hour (some function throughout the day, making 24 observations) and have an average of six recording instruments with daily graphics.

While collection is done by "DEPV," the data are being stored in "IAE-CTA."

"IAE-CTA" also has 32 telepluviometric stations in a relatively small area closeto Petrolina, Pernambuco, and Juazeiro, Bahia, as a followup to a research project on weather modification.

DNOCS

DNOCS had a network of hydrometric stations (some of which werethermopluviometrics), but the responsibility for operation was transferred to "SUDENE." DNOCS still collects data from pond basins and from representative river basins in the Northeast.

SUDENE

The "Divisao de Hidrometeorologia" (Hydrometeorology Division) of SUDENE operates, under an agreement with "INEMET", 103 main climatological stations in the area covered by this agency. The data are forwarded to INEMET. This division also operates the old DNOCS hydrometric network which now has 2006 stations; some were functioning in the last century (Fortaleza, Ceara, in 1849; Quixeramobim, Ceara, in 1896; Mossoro, Rio Grande do Norte, in 1899; Joao Pessoa, Paraiba, in 1893; Recife, Pernambuco, in 1842 and 1889; and Salvador, Bahia, in 1883). Of these, 151 operate rainfall recorders, 58 operate evaporimeters (pans), and 250 are fluviometric stations. "SUDENE" also operates networks in representative river basins, in which the number of stations is variable, depending on the river basin under study. Normally, those networks function for a 5-year period. Data are being processed by "SUDENE".

UFPb

The "Nucleo de Meteorologia Aplicade — NMA", UFPb (Applied Meteorology Center), in Campina Grande, Paraiba, has operated since 1973 a network of solarimetric stations in different regions of the State of Paraiba. Each station is equipped with a heliograph, an actinograph fortotal incoming radiation, and an actinograph for diffuse sky radiation. Besides these data, "NMA" has a general record of "INEMET" data.

UFCe

UFCe and other institutions operate different networks of agrometeorological stations in their respective geographical areas.

Altitude Data

The altitude data (radiosonde, pilot balloon, etc) are basically collected by the following organizations.

- Instituto Nacional de Meteorologia — INEMET, Ministario da Agricultura (National Meteorological Institute, Agricultural Ministry).
- Diretoria de Electronica e Protecao ao V6o — DEPV, Minist6rio da Aeronautica (Electronics and Flying Protection Management, Air Force Ministry).
- Instituto de Atividades Espaciais — IAE do Centro T6cnico Aeroespacial — CTA, "Minist6rio da Aeronautica" (Spacial Activities Institute of Technical Aerospacial Center, Air Force Ministry).
- Superintendencia do Desenvolvimento do Nordeste — SUDENE, Ministerio do Interior (Northeast Development Superintendence, Interior Ministry).
- Telecommunicacoes Aeronauticas S/A — TASA (Aeronautics Telecommunications Corporation).

The data collected by these organizations, as well as the detailed operations of each one, are described below.

INEMET/SUDENE

INEMET operates in the Northeast, under an agreement with SUDENE, 12 pilot balloon and 10 radiosonde-wind stations. Data are being processed by "INPE" and "IAE-CTA." Data collection started approximately in 1967; but most of the stations began functioning only around 1970. The original data are found in "SUDENE" headquarters in Recife.

DEPV/IAE-CTA

In the Northeast DEPV operates one radiosonde-wind station, in Natal, Rio Grande do Norte, and some pilot balloon stations. Data are being stored in "IAE" of "CTA," which is also processing them.

TASA

This agency collects altitude data from other institutions and those obtained from the commercial aircraft flying over the South Atlantic.

The Meteorological Situation in Northeast Brazil

Meteorological Network of Stations

The present status of the meteorological observations in Northeast Brazil is characterized by:

- Duplication of efforts by institutions, which hampers efficiency.
- Need for new and up-to-date equipment.
- A shortage of qualified personnel.

Agrometeorology

Systematic meteorological observations of interest to agrometeorology (excluding, therefore, those obtained from specific trials) are made in the Northeast, especially by the following organizations:

- Instituto Nacional de Meteorologia (INEMET), the National Meteorological Institute, with 103 climatological surface stations.
- Departmento Nacional de Aguas e Energia Electrica (DNAEE), the National Department of Water and Electric Power with pluviometric stations.
- Agricultural State Secretariats and the institutions linked to them which make up state networks of agroclimatological stations.
- Superintendencia do Desenvolvimento do Nordeste (SUDENE), the Northeast Development Superintendence evaporimetric and fluviometric stations.
- Departamento Nacional de Obras Contra as Secas (DNOCS), the National Department of Works Against the Drought, with its pluviometric network.

Defining the optimal distribution and density of the necessary network of meteorological observations is a matter of considerable complexity. Approaches should be related to the objectives to be reached. Thus the necessary network for weatherforecasting, for example, is not the same as that required for an agroclimatic zoning. In agrometeorology, the optimal density of a network in a given region depends on the intensity of the agricultural and livestock activities. Another important aspect is the necessity of planning long-range agrometeorological studies, since any activity to be carried out will depend on the availability of data over a reasonably long period. The following steps exclusively related to agrometeorology, will not remove the problem in the northeast, but will be very helpful in solving it:

- It would be convenient and efficient to complement the pluviometric stations, perhaps with maximum and minimum thermometers which require only a daily observation.
- A standardization of observation techniquesthroughoutthe networks under INMET supervision is required.

General Records of Data

Just as there is considerable variation in number and daily timing of observations, there is no standardization as to the processing of these data. Each institution which works with extensive series of data establishes, individually, its programs without close coordination with others.

Since the agrometeorological research will depend on the quality and standardization of information, it is suggested that the activities within this field should be centralized in order to obtain uniform processing of data.

Agrometeorological Research in the Northeast: The Present Situation

The information given here and in the following section was taken from a survey carried out by EMBRAPA.[5]

Situation in Brazil

Agrometeorological research started in Brazil around 1950, through the isolated efforts of some researchers from state and federal institutions located in the states of Rio Grande do Sul, Sao Paulo, and Bahia. In the last decade, the expansion of agriculture has increased the need

5. Projeto Nacional de Agrometeorologica (PNAM), EMBRAPA (preliminary paper), 1978.

for investment in agrometeorology, to study the influence of climatic elements on crop development and yields. Human resources received full support from 1974 on. Several Brazilian researchers have taken advanced courses abroad and the first postgraduate courses have been started in this country.

EMBRAPA's survey identified 34 institutions or centers, which are now starting or already carrying out agrometeorological research. These institutions are distributed among the different Brazilian regions, as follows: 2 in the North (Amazon), 4 in the Middle-West, 11 in the Southeast, 10 in the South, and 7 in the Northeast.

Situation in the Northeast

The institutions or centers now starting or already carrying out agrometeorological research in the Northeast—including those located outside the semi-arid zone — are:

- Centro de Ciencias Agrarias (CCA), Universidade Federal do Ceara UFCE (Rural Sciences Center, Federal University of Ceara).
- Centro de Ciencias e Tecnologia (CCT), Universidade Federal da Parai'ba — UFPb (Technology and Sciences Center, Federal University of Paraiba).
- Centro Nacional de Pesquisa do Algodao (CNPA/EMBRAPA) (National Cotton Research Center).
- Centro Nacional de Pesquisa de Caprinos (CNPC/EMBRAPA) (National Sheep and Goat Research Center).
- Centro de Pesquisa Agropecuaria do Tropico Semi-Arido (CPTSA/EMBRAPA) (Agricultural and Livestock Research Center for the Semi-Arid Tropics).
- Centro de Pesquisa do Cacau (CEPEC), Comissao Executiva do Piano da Lavoura Cacaueira — CEPLAC (Cacao Research Center, Executive Commission of the Cacao Farming Plan).
- Empresa Pernambucana de Pesquisa Agropecuaria, Secretaria da Agricultura do Estado de Pernambuco — SAG-PE (Agricultural and Livestock, Pernambuco Research Enterprise, Agricultural Secretariat of the State of Pernambuco).

However, few papers on climatology or agrometeorology in the Northeast have been published.

According to the available information, it is evident that most papers are related to the water balance on a regional basis. In the research institutions exclusively dedicated to a sole product, such as CEPEC-CEPLAC, several papers have been published on studies of plant-pathogen-environment interactions. At present, in the Northeast, three Centers stand out.

1. CCT-UFPb, through the Nucleo de Meteorologia Aplicada (Applied Meteorology Center), situated in Campina Grande, Paraiba, dedicated chiefly to studies on agroclimatic zoning, rainfall, and meteorological instrumentation.

2. CPATSA/EMBRAPA, located in Petrolina, Pernambuco, focuses its agrometeorological research on the analysis of the relations between climate, soil and plants in the semi-arid zones. Its objective is to select areas for introduction of dry farming, based on the quantity, intensity, and distribution of rainfall.

3. CEPEC-CEPLAC which, at present, confines its research in agrometeorology to the ecophysiology of the cacao tree and to the influence of meteorological elements on the occurrence of *Phytophtora palmivora,* which causes cacao fruit rot.

At other centers the activities in agrometeorological research are still in the planning phase, concentrating mostly providing specialized training for personnel and on obtaining up-to-date instrumentation for meteorological observation both in the laboratory and in the field.

Other Meteorological Research Important to the Northeast

The survey made by EMBRAPA also described other meteorological research activities besides those specific to agrometeorology.

Several institutions, though situated outside the Northeast, are doing research that is applicable in this region. Some of them are:

1. The Instituto Nacional de Meteorologia (INEMET),the National Meteorological Institute, with headquarters in Brasflia, Distrito Federal, is studying adverse

meteorological phenomena which include the occurrence of drought and flood. The first phase of this project covers statistical and probabilistic studies. Later there will be a synoptic-dynamic study to determine the conditions favorable to the occurrence of those phenomena.

2. The Instituto Nacional de Pesquisas Espacias (INPE), the National Institute of Space Research—linked to the Conselho Nacional de Desenvolvimento Cientifico e Tecnologico (CNPq), the National Council for the Scientifical and Technological development — with headquarters in Sao Jose dos Campos, Sao Paulo, has developed three programs based on reception of meteorological satellite signals. Two of these cover subjects important to the Northeast. The first is related to the systematic study of tropical atmospheric dynamics, aimed at numerical weather forecasting; local and the inter-hemispheric influences on Northeast weather are also being studied. The second is a study of Brazilian climatological characteristics and natural and manmade changes in them. Currently, the study emphasizes the analysis of climatic problem in the Northeast and the Amazon.
3. The Centro Tecnico Aeroespacial (CTA), the Technical Aerospace Center through the Instituto de Atividades Espacias (IAE), the Space Activities Institute — also located in Sao Jose dos Campos, Sao Paulo, makes continuous studies on artificial weather modification and on forecasting adverse meteorological phenomena. In the first case, the technical and economic feasibility of rainfall changes in Northeast through cloud seeding are being studied. In the second case, aerial photographs sent by meteorological satellites are being utilized to identify the possible correlations between tropical stratospheric oscillations and the rainfall regime in the Northeast.
4. The CCT-UFPb, through the NMA, started in 1976 to develop research directed towards Northeast problems. Among its meteorological research activities — in addition to those specifically related to agrometeorology — the following work deserves special mention:
   a. Study on the dynamic-synoptic status of the atmosphere in the Northeast with a goal of recognizing the meteorological systems that are acting in the region (case studies) to stimulate- or inhibit rainfall.
   b. Wind zoning of the Northeast with the aim of delineating areas with wind potential for power generation.
   c. Potential solar energy zoning in the Northeast for utilizing radiation from the sun as a power source through appropriate equipment (collectors, cells, stoves, distillers, dryers, etc.).
   d. In addition to its research the NMA has also developed a postgraduate program in (i) agrometeorology of semi-arid zones, and (ii) dynamics of the tropical atmosphere.

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Agricultural Meteorology in India: A Status Report

R. P. Sarker and B. C. Biswas*

Summary

The observational setup of agricultural meteorology in India and the collection, compilation, and documentation of data have been outlined. Information regarding preparation of crop-weather diagrams, crop-weather calendars, agroclimatic atlas, and rainfall publications has been given. The various types of rainfall analysis, including one for short-duration rainfall for a few stations of the semi-arid tropics of India, have been dealt with. Analyses of weekly probabilities of rainfall for dry farming districts of India and details of the same for Maharashtra and Gujarat have been discussed and their utility for agricultural planning has been brought out. Climatic classification for estimating the agricultural potential of a region on the basis of a Moisture Availability Index and water-availability period has been included. Studies on soil moisture, aridity, and drought indices; wet and dry spells; evaporation and evapotranspiration; crop-weather relationships; and preparation and issue of crop-yield forecasts have been outlined. The services rendered by the India Meteorological Department to agriculturists have also been described.

India's economy has for many years been agricultural in nature. Despite recent progress in industrialization, the soundness of its economy is significantly dependent on the gross production of agricultural commodities. The latter, in its turn, is influenced by the vagaries of weather. It is well known that yield from any given crop/variety depends on the extent to which certain optimum conditions of rainfall/ soil moisture supply, radiant energy, photoperiod, and temperatures are satisfied during different stages of crop growth. Weather can also indirectly affect crop production when weather situations (a) lead to the outbreaks of pests and diseases of crops, (b) interfere with timely agricultural operations and plant-protection measures, and (c) bring about deterioration in the quality of seed material held in storage. Hence, meteorological consideration becomes part of the realm of agriculture by its own right.

Meteorological studies and services can help bring about better agronomic practices in two broad ways. First, timely weather forecasts of short and medium range, would enable the farmers to adopt agricultural practices that minimize the adverse effects of weather and maximize its beneficial effects. Second, further scientific study of the interrelationship between crops and their environment would aid in the development of better varieties and in the proper choice of crops and farming practices. Meteorological studies can also help long-term agricultural planning, by identifying regions of similar climate and delineating areas subject to different intensities of weather vagaries.

In the following paragraphs we give a brief status report of Agricultural Meteorology in India including the various research activities aimed at betterment of agricultural planning and practices.

Organization

Network of Observatories and Collection of Data

The India Meteorological Department, since its inception in 1875, has helped agriculturists. However, a Division of Agricultural Meteorology was started by the India Meteorological Department in 1932 to cater exclusively to the needs of agriculturists and to conduct research

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on plant-weather relationships. A major step was taken in the early forties to set up specialized meteorological observatories in a crop environment to inculcate weather consciousness amongst agriculturists and to develop farm environment climatology. This has resulted in a steady growth of observatories, which at present number about 125. Besides agromet observatories, synoptic weather stations also record data such as rainfall, temperature, radiation, low level wind, evaporation, etc. These are equally useful in agriculture.

The National Commission on Agriculture recommended establishment of Principal Agromet observatories in each of the Agricultural Universities. The Indian Council of Agricultural Research (ICAR) has recently sanctioned 52 Principal Agromet observatories in 21 Agricultural Universities and 31 Research Institutes and Crop-Coordinating centers functioning under ICAR. An ambitious network of a minimum of two Agromet observatories in each district, totalling about 600 observatories all over India, is being contemplated and efforts are being made to attain this goal in the near future.

The number of stations recording different observations and instruments used are given in Table 1.

Data Punching and Verification

The India Meteorological Department has been observing and storing meteorological data with meticulous care for more than 100 years for the purpose of building a good data bank of climatological information. With this end in view, the Department started the systematic transfer of data from manuscript form to punch cards around 1945, carefully scrutinizing and correcting the data before punching. Transfer of data to punch cards started for upper-air observations in 1945, for rainfall in 1950, and for surface meteorological observations in 1969. The present holdings of data include more than 37 million punched cards, of which the agromet data account for approximately 6 million, rainfall data for approximately 8 million, upper-air data 5 million, marine data 3 million, and so on. This holding is further accumulating at approximately 2.3 million cards every year. This enormous and ever-increasing volume of meteorological information is already posing complex problems of storage and quick retrieval. It may be noted that while daily values of all meteorological elements are punched, both daily and weekly values for agromet data are available on punched cards. In addition, crop

Table 1. Network of agrometeorological observatories in India.

Data recorded	Observatories (no.)	Instrument used[a]	No. and time of observations
Rainfall	About 5000	Raingauge	0830 hr IST
Max temperature Min temperature Dry bulb temperature Wet bulb temperature	535 approx.	Thermometer	0700 and 1400 hr L.M.T.
Wind speed and direction	535	Windvane	0830 and 1730 hr IST
Soil moisture	17	Gravimetric method	Once in a week/fortnight.
Soil temperature	62	Soil thermometer	0830 and 1730 hr IST
Dew (5, 25, 50, 150 cm)	97	Dew Gauge	Before sunrise
Radiation	41	M.G. solarimeter, etc.	Continuous
Evaporation	198	Class-A pan	0830 hr IST
Evapotranspiration	35	Lysimeter	0830 and 1730 hr IST
Grass min. temperature	6	Grass min. thermometer	0700 hr L.M.T.
Sunshine	94	Sunshine recorder	Daily total

a. Self-recording observations by thermograph, hygrograph, and self-recording raingauge are also maintained in important principal observatories.

elements are kept in registers.

At one time, the data were processed on the tabulator, sorter, and collator. In 1964, the India Meteorological Department acquired a second-generation computer system, the IBM-1620. With its acquisition, the use of computer methods in data scrutiny and electronic data processing had come to stay. In 1973, the Department purchased another computer, an IBM-360/44, mainly for operational work and for research, and installed it in New Delhi. In 1977, the Department took another leap forward and acquired a new computer system EC-1040 mainly for climatological work. It is a modern third-generation computer system with a memory of 256 kilobytes (characters) and an average processing speed of approximately 400 000 operations per second. It has been decided to transfer all the present data holdings from the punched cards to magnetic carriers with the use of this computer system. It has been estimated that it will take approximately 4 to 5 years to put all the data on to tapes, which would then be numbering several hundreds.

The processed agrometeorological data are used in a variety of ways in addition to research. For example, these are used for preparing the crop-weather diagram, the crop-weather calendar, and the agroclimatic atlas.

Crop-Weather Diagram

Normals of meteorological parameters and crop characteristics are presented in these diagrams. These yearly diagrams give information on major crops grown at different stations during the year. Crop performance and the weather experienced during the season are displayed side by side, along with their normal/average values. These are useful in comparing growth behavior of the crop with the effects of weather.

Crop-Weather Calendars

Agriculturists require advance warnings of hazardous weather for various agricultural operations. To meet these requirements, crop-weather calendars are prepared for the important crops grown in the various districts of India. These calendars give, in an easily understandable form, the weather conditions detrimental to the various phases of growth of the crops and are based on information received from agricultural authorities and the knowledge of the normal weather conditions. These calendars (about 500) serve as a guide for issue of warnings to farmers. Guides are also prepared for new varieties of the standard crops.

Agroclimatic Atlas

The Agroclimatological Atlas of India has been printed. Agroclimatic parameters such as rainfall, air temperature, humidity, grass minimum temperatures, soil temperature, soil moisture, solar radiation, sunshine, evaporation, thunder-storm, hailstorm hazards, and wind patterns collected from Agromet and departmental observatories have been put in their best representative forms in this atlas. This is expected to be of great help for plant breeders and other agricultural scientists for various types of agricultural planning.

Analysis of Data for Agrometeorological Purposes

Data collected and documented previously are analyzed for national developmental purposes, including agriculture. Considerable work has been done in India in this respect. In the following paragraphs, we enumerate some of these analyses. Of all the meteorological elements, rainfall is the most important, so we devote more attention to various rainfall analyses.

Rainfall

Today, there are more than 5000 raingauge stations spread over the country; with these rainfall measurements taken systematically under standard exposure conditions. In addition, there are nearly 3000 additional raingauge stations in the country, maintained by the railways, irrigation, forestry departments, and other agencies for their specific needs. There are about 400 self-recording raingauge stations functioning at river basins and other parts of the country. Data collected are regularly published for use by investigators.

Rainfall Publications

The IMD has brought out many useful publications on rainfall. Monthly and annual normals of *rainfall* and of *rainy* days, based on data from about 2700 raingauge stations operating in India during 1901 to 1950 have been brought out in the Memoirs of the India Meteorological Department.

The Rainfall Atlas of India, also based on the 1901-1950 data, was published in 1971. This contains various charts for rainfall, rainy days and their variability for monthly, seasonal, and annual periods. A detailed rainfall atlas is being prepared for publication.

Monthly and annual rainfall and the number of rainy days occurring each year from 1901 to 1950 for about 2700 raingauge stations have been printed in five volumes.

Daily accumulated normals for about 400 stations have been published.

Climatological tables of observatories in India (1930-1960) have been published. These contain rainfall, rainy days, temperature, humidity, pressure, wind, and cloud information.

Frequency distribution of daily rainfall for 342 selected stations in India, based on records for the period 1901-1950, is under print.

Some Important Results of Rainfall Analyses

On the basis of rainfall data of the 60-year period (1901-1960) for about 3000 rainfall stations it was learned that mean annual rainfall of India (outside Pakistan and Bangladesh) is of the order of 119 cm and the rainy season rainfall (i.e., Jun to Sep) accounts for about 75% of this mean (Dhar et al. 1974).

On the basis of the examination of a largevolume of self-recording rainfall data, the average time distribution of short-duration rainfall was found to be as follows:

1 hour	max. rainfall	is about	30%	of the 1-day rainfall
2	"	"	40%	" "
3	"	"	50%	" "
6	"	"	60%	" "
12	"	"	75%	" "
18	"	"	85%	" "

Nomograms have been prepared to help estimate 1-day rainfall for individual stations in the meteorological subdivisions of northern India for the low-return periods of 2, 5, 10, and 25 years; this is done from the respective mean annual rainfall value of the station concerned. The relationship holds good for plains stations (Dhar et al. 1971).

Extreme annual 1-day rainfall values of four SAT stations — Anantapur, Hyderabad, Bellary, and Sholapur— have been computed with the 1901 to 1960 data. Gumbel's (1954) extreme-value distribution as modified by Chow (1953, 1964) has been used for the analysis. Table 2 gives the results for different return periods.

Based on self-recording rainfall data, return-period values of rainfall for short durations of 5, 15, 30, and 60 minutes have been computed (Table 3) for two stations.

Rainfall Probability Analysis

The dry-farming tract of India, where annual rainfall varies from 400 to 1000 mm, includes 87 districts in nine states. This practically covers the whole semi-arid area of India. In order to

Table 2. One-day rainfall magnitudes (cm) for different return periods.

Station	Return period						Highest 1-day observed rainfall	Return period of highest 1-day observed rainfall
	2-year	5-year	10-year	25-year	50-year	100-year		
Anantapur 14°41'N, 77°37'E	7.5	9.8	11.3	13.2	14.7	16.1	14.5	46
Hyderabad 17°27'N, 78°28'E	7.0	9.7	11.5	13.6	15.3	16.9	19.1	255
Bellary 15°09'N, 76°51'E	7.0	9.6	11.4	13.6	15.2	16.9	16.2	72
Sholapur 17°40'N, 75°54'E	8.0	10.7	12.7	15.0	16.8	18.5	19.1	121

Table 3. Rainfall intensities (mm/hour) for various durations and recurrence intervals at two stations.

PUNE (18°32'N, 73°51'E)

Duration (minutes)	Recurrence interval (years)					
	2	5	10	25	50	100
5	107	134	163	191	211	231
15	75	102	119	141	169	176
30	54	73	86	102	11.3	148
60	34	75	57	69	78	86
HYDERABAD (17°21'N, 78°28'E)						
5	96	120	131	144	159	168
15	72	92	104	120	132	144
30	55	72	84	96	106	116
60	36	54	65	79	89	100

determinethe climatic potential of this area as it regards agriculture, weekly rainfall data have been statistically analyzed by using the incomplete gamma distribution. The minimum assured rainfall has been established at different probability levels (Sarker et al. 1978). Some of the important aspects resulting from this analysis include:

- The minimum assured rainfall distribution at 50 and 70% probability levels have enabled classification of the entire dry-farming tract into seven broad homogeneous rainfall zones, and the duration of cropping season in these zones has been indicated.
- The analysis has enabled thedelineation of the drought-prone area; extending from Madurai(14°41'N,77°37'E)toAhmednagar (19°05'N, 74°55'E) via Mandya, Chitradurga, Bellary, and Bijapur. This area shows up distinctly in the 50 and the 70% rainfall charts. It appears difficult to raise a rainy-season crop in this area, but the prospect of a crop during the postrainy season is fairly good.
- The main rainfall zone during the period preceding the rainy season is in in the area near Bangalore (12°58'N, 77°35'E) in Karnataka during the 22nd week (28 May-2 Jun). With the progress of the monsoon, the main rainfall belt shifts to the north to the area of southern Gujarat adjoining parts of Madhya Pradesh and Maharashtra in the 30th week (23-29 Jul). Rainfall activity throughout the dry-farming tract is maximum in this week. After the 36th week (3-9 Sep), rainy-season activity increases in Andhra Pradesh and adjoining Maharashtra. With the withdrawal of the rainy season, the zone shifts to the south.
- In mid-season, the rainfall activities are lowest during the weeks 32 to 34 (6-19 Aug) throughout the dry-farming tract. It is likely that the rainy-season crop in many regions will suffer water stress during this period.

Similar analysis for Maharashtra (Biswas et al. 1977) and Gujarat (Biswas et al. 1978) has been completed, using a large number of rainfall stations. The important results are given below.

MAHARASHTRA. Three distinct rainfall patterns are observed in Maharashtra. In southern Maharashtra, the highest rainfall peak is found in the 38th week (17-23 Sep). In central Maharashtra, two similar peaks are noticed in the 26th (26 Jun-1 Jul) and the 38th weeks (17-23 Sep), with an intervening lull of 6 weeks. In northern Maharashtra,thefirst peak occurs in the 28th week (9-15 Jul) and is very prominent; the second peak (36th week, 3-9 Sep) is less prominent. However, a lull period of 1 to 2 weeks can be expected around the 33rd week (13-19 Aug).

The drought-prone area of Maharashtra State is identified as a zone comprising the northern part of Sangli, southern part of Sholapur, southern part of Ahmednagar, and adjoining areas of Pune and Satara districts.

GUJARAT. Gujarat may be divided into four parts, according to its rainfall pattern. In the east, the highest peak is observed during the 30th week (23-29 Jul). Main rainfall is spread from the 26th to the 36th week (25 Jun-9 Sep), with a lull period around the 32nd week (6-12 Aug). In this area, a rainy-season crop of 14 to 16 weeks duration may be raised once in 2 years. The highest assured rainfall peak in the second and third areas is in the 28th week (9-15 Jul). Rains may be expected from the 26th to 35th week (25 Jun-2 Sep) and the 26th to 33rd weeks (25 Jun-19 Aug) in the second and third areas, respectively. In the fourth area — the Kutch area — annual rainfall is less than 400 mm and rainy-season activities are experienced mostly in the 27th to 31st weeks (30 Jul-5 Aug). Rainfed agriculture normally does not flourish in this area.

A large area of low assured rainfall includes Ranpur, Chuda, Dhanduka, and Dholera; small areas of low assured rainfall may be observed around Amreli and Sanand, also.

It is clear from the above that while the analysis on an all-India scale gives a gross picture of agricultural potential, detailed analysis for smaller areas, such as states with a dense network of rainfall stations is essential for specific crop potential and agricultural management.

Moisture-Availability Index and Water Availability Period

The quantum of assured rainfall by itself does not indicatetheamount of water availabletothe plant, because the same amount of rainfall can act differently, depending upon the atmospheric demand of the site. The concept of moisture availability index (MAI), which may be defined as the ratio of assured rainfall to potential evapotranspiration, can give a better idea of availability of water to the plant. Hargreaves (1974) used the MAI concept to classify the Brazilian northeast, using monthly assured rainfall at the 75% probability level. As a month is a long period, weekly calculation of MAI is to be preferred. Sarker et al. (1978) used the weekly MAfto estimate the agricultural potential of some selected stations of Rajasthan, and a detailed study has been further extended over Maharashtra and Gujarat (Biswas et al. 1978). In this study weekly rainfall at the 50% probability level was examined and the periods with MAI greater than 0.3 were considered suitable for growing a crop. From these studies, water-availability periods of different categories may be estimated on the basis of MAI, to determine the maximum possible crop life cyclefor a given rainfall distribution.

Such processed information, when superimposed on soil type, will lead to the delineation of agroclimatic zones and subzones. These studies can also help to delineate regions and periods in which supplementary irrigation should be provided on a priority basis.

Table 4 presents MAI and water-availability periods for five typical SAT stations at the 50% probability level.

At Sholapur, although MAI is more than 0.3 for 17 weeks, a crop of 17 weeks duration cannot be raised, as the 70% water requirement by crops is satisfied only for 3 weeks. At the same time, a crop of 15 weeks duration may easily be harvested at Hyderabad, because the crop may

Table 4. MAI and water-availability periods for five SAT stations at 50% probability level.

Station	Latitude	Longitude	Weeks with MAI of:				Accumulated assured rainfall (mm)
			3≥.30	≥.05	≥.07	≥.09	
Sholapur	17°40'N	75°54'E	17	7	3	2	330
Hyderabad	17°27'N	78°28'E	15	13	8	5	406
Jejuri	18°17'N	74°10'E	9	2	2	0	176
Udaipur	24°35'N	73°42'E	13	10	7	6	314
Bhuj	23°15'N	69°48'E	2	0	0	0	48

get 70% of its required water for 8 weeks, 5 of which provided the full requirement. It may be mentioned that annual rainfall at these two stations is almost the same. It may be very difficult to raise a nonirrigated short-duration crop at Jejuri once in 2 years. At Udaipur, a crop of 13-week duration may be planned, as suggested by different categories of MAI and 314 mm assured water. A rainfed crop at Bhuj once in 2 years is speculative. Thus, the duration of the water-availability period is seen to differ significantly among the stations within a common climatic zone and of the same annual rainfall.

Dry and Wet Spells

In the semi-arid tropics, mid-season risks to crops often arise due to prolonged rainless spells. With this in mind, frequency tables of probability of runs of dry and wet spells have been worked out. Work has been done to examine the runs of dry and wet weeks in Gujarat and Maharashtra (Khambete et al. 1978). In Gujarat, the mean length of dry spell varies from 2 to 3 weeks. A similar study has been made on a daily basis for Maharashtra and Bihar (Chowdhury et al. 1978). The conditional probability has also been obtained by employing the Markov Chain Model (Chowdhury et al. 1978; Virmani et al. 1978).

Soil Moisture

In each of the broad climaticzones, a knowledge of the patterns of soil-moisture accumulation and distribution from rainfall in various types of rainfall years is vital for designing effective agronomic operations.

Soil-moisture data of a few stations, where reliable data for longer periods are available, have been analyzed and have revealed many interesting features of agronomic utility (Biswas, 1978). The meager soil-moisture observations available are not sufficient to define the moisture status of the country. It becomes necessary to evolve different methods to estimate soil moisture in various types of soil. Weekly changes in soil moisture from a cropped soil column have been computed from weekly rainfall, potential evapotranspiration, and ratio of actual to potential evapotranspiration, following the method suggested by Baier (1969). The estimated soil moisture of three stations of different climatic and soil zones have been varified with recorded soil-moisture data, and the estimations are within reasonable accuracy (Biswas et al. 1977).

Soil moisture in the deeper layers has been computed on the basis of the moisture content of the surface layers and compared with the actual observation. Regression equations connecting deeper depths and surface-layer soil moisture have been formulated for some stations (Biswas et al. 1977).

Another method of estimating the accretion of productive soil-moisture storage from daily rainfall and pan-evaporation data, after allowing for evaporation and runoff losses has been reported by Venkataraman (1973).

Water Requirements of Crops

In irrigated areas, the strategy is to maximize crop yields by optimum use of irrigation water. In the dry-farming tract, it is essential to practice the utmost economy of water use. It is therefore necessary to obtain data on water requirements of various crops during their different phases, under different meteorological conditions in different agroclimatic zones. Work has been started in the India Meteorological Department to determine experimentally, by the use of lysimeters, the daily evapotranspiration loss from a network of 35 stations covering major soil-crop-climate regions. Evapotranspiration data so far collected have been analyzed and some results of agronomic significance have been obtained for few crops (Sarkeretal. 1976; Venkataraman et al. 1976; Subba Rao et al. 1976). Details of these results will be presented by Dr. Venkataraman at this workshop.

Evaporation Distribution

Pan evaporation and PET give a measure of drying power of the air and are the most useful meteorological parameters for determining water requirements of crops. Evaporation is recorded at about 200 stations, using standard U.S. (Class A) evaporation pans, covered with wiremesh. The data have been compiled and published by the IMD. Monthly analysis of evaporation shows clearly the pockets of high and low evaporation zones during different seasons (Rao et al. 1971). The highest pocket of evaporation in all the months is over Saurashtra.

Estimates of potential evapotranspiration (PET) by Penman's method have been computed for about 300 stations (Rao et al. 1971) and monthly maps have been published.

Crop-Weather Relationships and Crop Yield Forecast

Crop growth and crop yield are profoundly influenced by the weather elements. The India Meteorological Department has carried out a number of investigations to define the relationship between crop characteristics and different meteorological parameters, utilizing data collected for wheat, jowar (sorghum), paddy, sugarcane, and cotton. The initial analysis was made by simple and partial correlation techniques. Similar analyses have been made at other agricultural institutions/universities. However, the response of crop to weather changes is not so simple as to be described by linear correlations; hence, investigations were made using curvilinear analysis, which not only shows which meteorological parameter is important for a particular crop phase, but also shows the optimum value of the parameter. This method has been found very useful for crop-yield forecasts.

In 1924 Fisher developed a technique to evaluate the effect of distribution of a meteorological parameter on a crop characteristic. This method is quite useful and has been extensively used by many workers (Gangopadhyaya et al. 1964; Srinivasan, 1973; Gildayal et al. 1975). Analysis by this method shows when a particular parameter — e.g. rainfall — is beneficial tothe crop and when it is detrimental. The method, however, becomes quite complicated when the combined effects of additional parameters are to be examined. We are at present examining the combined effect of two meteorological parameters using a method developed by Tippet (1926).

Having thus obtained some idea about crop-weather relationships, the India Meteorological Department has ventured to develop crop-yield forecasting models in terms of meteorological parameters. The preharvest forecast of crop yield will enable Government agencies to make policy decisions on food imports/exports and on internal food distribution. The technique involves identification of any significant correlations between yield and weather parameters and, on the basis of the parameters so identified, a multiple-regression equation is established for forecasting purposes. Recent advances in the field of agricultural technology have resulted in a steep rise in the crop yield. Technological trends have thus been introduced into the regression analysis, along with the meteorological parameters. Agricultural scientists are consulted during development of the forecast models. Almost the entire portion of the country where paddy and wheat are grown has been covered by the formulation. Some models have also been developed, on a district-wise basis, for crops normally grown in the dryfarming tract. At present, we are forecasting, on an experimental basis for rice and wheat.

Weather and Crop Pests and Diseases

Pests and diseases are yet another cause of low yields in India. The incidence and spread of pests and diseases are closely related to prevailing meteorological conditions, such as temperature, rainfall, and humidity. Realizing the importance of meteorology in the development of warning systems for alerting farmers to pest and disease outbreaks, the India Meteorological Department has undertaken a scheme on pest and disease meteorology. Studies are in progress on the relation of weathertothe incidence and spread of ergot of pearl millet, late blight of potato, the paddy stem borer, and the leaf spot disease of groundnut.

Service to Agriculturists

In addition to rendering advice from time to time on demand, the India Meteorological Department began, in 1945, to offer a regular weather service to farmers. Farmers' Weather Bulletins (FWB) are issued by the department's forecasting offices. Bulletins are broadcast daily in 20 regional languages on 59 All-India Radio stations. Information on the weather expected in the district during the next 36 hours is reported, together with the outlook for the 2 days following. Warnings are issued for squalls, hail storms, frost, and low or high temperatures. In this respect, the forecaster is guided by crop-weather calendars prepared by the Departmen for district-wise principal crops.

These bulletins are useful, but they are very general in nature because they cover large areas, and thus cannot include specific adviceto farmers. To make the service more user-oriented, the Agrometeorological Advisory Service Scheme has been started. The scheme envisages framing and issue of specific advisories to cultivators after a joint discussion between meteorologists and agriculture specialists. The dissemination of such advisories will be undertaken through the Farm Radio Service and in audiovisual form by telecast, wherever possible, once or twice a week.

Conclusion

The sustained efforts of the India Meteorological Department have been successful in making the agricultural research worker and the agricultural planner weather-conscious. Agricultural meteorology in India is nowpoised to meet new and exciting challenges, requiring closely coordinated and collaborative work among diverse agricultural interests in the application of meteorological knowledge to crop planning, land use, water management, and agronomic practices — including scheduling of irrigation and plant-protection activities on a more scientific basis. We have geared up our present activities and drawn up plans to meet these new and exciting challenges.

It is hoped that this report will stimulate discussion and help identify areas where agroclimatological research is needed most. It is considered essential that various research institutes join together and undertake collaborative projects, so that increased agricultural production becomes a reality in the SAT in the near future.

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Classification of Climate and the Potential Usefulness of Pattern Analysis Techniques in Agroclimatological Research

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Summary

Climate classification has been of historic importance in developing a broad understanding of factors affecting soil and crop patterns in various environments. Many climate classifications have been published using various approaches. Most classifications have been macro in concept and have usually been applied on a continental or global basis. With the increased availability of numeric data and the development of computers and pattern analysis methods, new approaches in classification of climate are possible. In particular classification of micro-, as well as macro-, environments is possible.

In this paper, following a broad view of past climatic classification, the application of pattern analysis methods to climatic data is discussed and advantages and disadvantages of the approach noted. Emphasis is given to the use of similarity measures rather than to ordination techniques and the use of both Euclidean distance and Canberra metric coefficients in relation to climatic data is considered. Choice of climatic attributes used in an analysis is affected both by the purpose of the analysis and by the availability of data.

Five main uses of pattern-analysis techniques in agroclimatological research are discussed. These are 1) classification of climate, 2) detection of homoclimates, 3) grouping of experimental areas and locations, 4) geographic extrapolation of experimental results, and 5) domain definition. Pattern-analysis techniques are likely to be most useful in comparisons of specific areas for clearly defined purposes rather than in the development of continental or global classifications.

A/though numerical methods used in pattern analysis are still evolving, the main challenge in agroclimatological research is at the climate-plant interface; much better definition is required at this level.

Increasing use is being made of climatic data in agricultural research. In addition to traditional uses, such as in the definition of single environments and in climatic classification, there is a greater awareness that more precise measurement of the climatic environment is a key factor in the quantification of plant behavior and in understanding variations in plant growth in diverse environments.

Agroclimatological research and development have considerable potential in the less well-defined subtropical and tropical environments of the world. Here, in addition to the need for increased agricultural production, there is scope for better definition of useful tropical crop and pasture plants, for transfer of information between similar homoclimates, and for planned plant introduction between environments. There is also a need, in agroclimatological research generally, for techniques that will group experimental areas and locations and thus perhaps enable the extrapolation of experimental results from one area to another.

Classification, or the grouping of similar entities, has an important contribution to make to all of these needs. In particular, pattern analysis is a technique that has value in classification and in making use of the large amount of climatic data currently being collected, in addition to the large amounts of historical data available in many parts of the world.

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Classification of Climate

The classification of climate became fashionable in the latter half of the nineteenth century. This arose from the increase in geographic knowledge of the world and the increasing availability, on a global scale, of climatic data on rainfall and temperature. Much of this emphasis on climatic classification was in the search for universal criteria that could integrate available environmental information and predict the usefulness of developing agricultural areas in North and South America, Africa, and Australasia.

In the century since, a large number of classifications of climate have been proposed. Gentilli (1958), for example, noted that 75 classifications or partial classifications had been proposed. In a later paper (Gentilli 1972), he gives details and maps of 15 climate classifications of the Australian continent, all of them macro in concept and divisive in approach. These classifications can themselves be classified in relation to the climatic criteria used (Table 1).

A chronological listing of some of the different approaches to the classification of climate that have been proposed are presented in Table 2. The two global classifications most widely cited are those of Koppen (1936) and Thornthwaite (1948). Both are quantitative, and the increased availability of climatic data with time has made possible the more accurate delineation of their boundaries. Both classifications make use of integrated climatic elements and single-value indices.

A more recent classification is that of Papadakis (1966). This classification is very much oriented towards agricultural and crop requirements, with the limiting criteria chosen to represent values of significance for crop plants. In this classification, account is taken of climatic characteristics such as mean annual minimum temperature, frost-free season, average daily maximum or minimum temperature for key months and periods of the year, water balance, and the occurrence of dry and wet seasons.

Although a large number of climatic classifications have been proposed, no universal system to compare, for example, with the Linnean plant system, has emerged. Part of the difficulty in classifying climate is that it forms a continuum varying in time and space. Also, past climate classifications have tended, through necessity, to be divisive and based on perceived most-important criteria comprising a few variables.

The purpose of this paper is not to evaluate published classifications; rather it is to discuss the potential usefulness of pattern analysis as a technique in grouping similar climatic environments.

Table 1. Classification of criteria used in climatic classifications.

Time	Frequency or duration	Climatic elements	Examples of criteria
Independent		Single	Temperature
			Rainfall
			Wind direction
		Combined	Temperature and rainfall
		Ratios	Temperature/rainfall
			Rainfall/evaporation
Dependent	Frequency or probability	Single	Annual wet days
			Percentage wet days
		Combined	Wet days with certain wind pattern
			Temperature and humidity
		Ratio	Frequency of years with R/t+10>0
			Probability of years r<t+7
	Seasonal duration	Single	Frost-free season
		Ratio	Months r/e .75>.4

Source: Gentilli (1972).

Table 2. Published climatic classifications and main criteria used.

Author(s)	Year	Main criteria used
Voeikov	1874	Seasonal incidence of rainfall
Herbertson	1905	Combination of rainfall and temperature
DeMartonne	1909	Combination of rainfall and temperature
DeMartonne	1948	Index of aridity
Hunt, Taylor, Quayle*	1913	Seasonal rainfall
Kdppen	1918	Annual and monthly means of temperature and rainfall
Koppen	1936	
Thornthwaite	1931	Temperature and humidity using P/E
	1948	Temperature and potential evapotranspiration
Hettner	1934	Zonal winds
Prescott, Trumble, Davidson*	1934	Precipitation/evaporation indices
Prescott, Trumble, Davidson*	1949	Precipitation/evaporation indices
Andrews and Maze*	1933	Intensity of aridity
Cur6*	1945	Combination of temperature and rainfall
Creutzberg	1950	Duration of humid months
Bagnouls and Gaussen	1953	Rainfall-temperature Index
	1959	Rainfall-temperature Index
Walter, Leith, and Rehder	1960	Thermohydric criteria
Hendl	1963	Atmospheric circulation
Meher-Homji	1963	Rainfall-temperature Index
Troll	1964	Duration of humid months
Papadakis	1966	Water, heat thresholds related to crop growth
Fitzpatrick and Nix*	1970	Growth index
McBoyle*	1971	Factor analysis, twenty attributes
Russell and Moore*	1976	Sixteen climatic attributes on annual and seasonal basis

* Classifications of Australian climate only

Pattern Analysis

Pattern analysis methods have greatly affected classification in various scientific fields. Their value has been greatest in areas such as microbiology, where previous classifications based on large numbers of criteria were unstable and unsatisfactory.

Most of the previous climatic classifications have relied on a few key variables and specific divisions made in what are frequently continuous variables — e.g., Koppen (1936) used 5°, 10°, 18°, and 22°C as important criteria for separating different climates on the basis of temperature. The development of large computers and numerical methods allows many more variables to be included. Shorter time periods can now be considered — an approach developed only in a rudimentary seasonal form in previous classifications. This is particularly important in considering the growth of many crops whose life span may be less than 100 days and where knowledge of the climatic environment may be limited to short periods.

Almost all previous classifications have been divisive in splitting from above into groups on the basis of certain criteria. While this approach is possible with numerical methods, and programs are available to do this (e.g. POLYDIV, Milne, 1976), numerical methods also allow an agglomerative approach from below.

Numerical methods are objective in the sense that with a given set of data and a given procedure the resulting groupings are reproducible. Although emphasis in most numerical methods is laid on the lack of weighting of different attributes, explicit weighting can be used if desired. In addition, most commonly used numerical procedures show hierarchical relationships between groups, so different levels of agglomeration can be examined.

Disadvantages of pattern analysis are related to the extent to which classifications are method-dependent. Studies in other fields suggest that, with appropriate methods, classifications can be meaningful and stable (Moore and Russell 1967; Moore et al. 1972). Climate classifications are also attribute-dependent, and the choice of attributes will largely affect the classification obtained. In some situations information is so scarce that all available data should be used. This is the approach that has been applied in a recent paper by Russell and Webb (1977), where the only available climatic data for a series of stations was monthly rainfall and maximum and minimum temperatures. Daylength could be determined from the station location, which meant that 48 attributes were available on an annual basis. However, the classification obtained was meaningful in relation to other data on grass and legume species grown at these stations.

Pattern Analysis Methods

The two main pattern analysis approaches that can be used in the study of climate are 1) classification using similarity measures, and 2) ordination using a variety of analyses, including principal component analysis and principal coordinate analysis. In this paper reference will be made only to similarity measures.

A very large number of similarity measures have been proposed in the literature (Sneath and Sokal 1973). On the basis of research on a number of coefficients (Moore and Russell 1967), two have been found to be useful in the classification of climatic data. These coefficients are Euclidean distance and the Canberra metric.[1]

Euclidean distance requires standardization to unit variance to eliminate effects due to the choice of units used in measurement. This is obtained by the relationship

$$x' = (x - \bar{x})/SD$$

where x' is the standardized attribute value, x is the overall mean of the attribute in question over all stations, and SD is the standard deviation. This coefficient has been used in a number of climatic analyses (Russell and Moore 1970; Russell and Moore 1976a, 1976b).

The Canberra metric has been found to have particular valuewith climatic data. The metric is the ratio of the absolute value of the difference between two attribute values over the sum of the attributes. For any two stations these ratios are summed over all attributes. The Canberra metric is constrained between 0 and 1. Because attributes occur in both the numerator and denominator, standardization to eliminate the effects of units is not necessary. The Canberra metric also has been found to be less affected than Euclidean distance by outlier values (Russell and Moore, 1970), and this is an important characteristic in the classification of climate.

Following the use of comparisons between stations using a similarity coefficient, a triangular similarity matrix is obtained with n(n-1)/2 values where n is the number of entities (in climate, these are usually stations) based on a certain number of attributes.

It is then necessary to sort this triangular matrix and obtain a dendrogram showing a hierarchical relationship between entities. Various strategies — centroid, nearest-neighbor, further-neighbor, etc. — can be used to do this. To some extent the methods used are dependent on the coefficient used. Many of the sorting methods used can be expressed in terms of the general linear model (Lanceand Williams 1967).

$$d_{hk} = \alpha_1 d_{hi} + \alpha_2 d_{hj} + \beta d_{ij} + \gamma |d_{hi} - d_{hj}|$$

where i and j are two groups of individuals to be fused into a new composite group (k); a further outside group, h, is not involved in this fusion. The d values are distances between the various groups.

For the classification ot climatic data, the flexible strategy has been found to be satisfactory. Values of the parameters for the flexible strategy are $\alpha_1 + \alpha_2 + \beta = 1; \gamma = 0$. It is completely defined by β, the cluster-intensity coefficient. For most data, a value of $\beta = -0.25$ appears satisfactory.

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1. $$\text{Euclidean Distance} = \left[\frac{1}{m}\sum_{j=1}^{m}(x'_{1j} - x'_{2j})^2\right]^{1/2}$$

$$\text{Canberra Metric} = \frac{1}{m}\sum_{j=1}^{m}\left(\frac{|x_{1j} - x_{2j}|}{x_{1j} + x_{2j}}\right)$$

where x_{ij}. is the jth variate for the ith unit, x'_{ij} is the corresponding standardized variate and m is the number of attributes.

Choice of Attributes

The choice of attributes which should be used to describe climate inevitably arises in any climatic-pattern analysis. Where a general description of climate is sought, it is probably desirable to use as many attributes as possible. The data available obviously influence the attributesused. Geographically, thewiderand more extensive the study, the less the chance that a large number of equivalent measurements will be available for all stations.

The basic attributes used in most of the published examples of pattern analysis have been monthly means, such as rainfall and temperature (e.g. Kyuma 1972), or monthly extremes, such as maximum and minimum temperature. Attributes that were used in a study of comparative climates of that part of Africa in the southern hemisphere, and of Australia, New Guinea, and New Zealand (Russell and Moore, 1976a) are presented in Table 3.

Most of the attributes are measured values, which are the usual means of standard meteorological measurements taken over specific intervals. Some of the attributes were derived from measured data — e.g., degrees of frost, rainfall/wet day. Monthly daylength could be calculated for each station on the basis of its latitude.

In using event attributes, such as lowest absolute temperature, length of record assumes importance. The length of records of stations being compared can vary markedly. This effect is likely to be most important in stations with short records.

The balance of attributes, e.g., rainfall vs temperature, is clearly important in the groupings obtained. Little information is available on the effect of different suites of attributes. Russell and Moore (1976b) examined two separate classifications achieved by using available data in northern Australia comprising:

1. Broad spectrum of climatic attributes, including rainfall and temperature, with both means and event measurements (59 stationsx 192 attributes).
2. Rainfall measurements only, first, third, fifth, seventh, and ninth deciles of monthly rainfall (254 stationsx 60 attributes).

Although there were broad similarities between the groupings, differences obtained were also apparent in particular localities. One advantage of the greater number of stations is that it shows a more complex pattern which, in coastal and mountainous regions, is much closer to reality.

It is likely that, for general-purpose classifications there will be an evolutionary change in attributes with time. For such classifications it can be argued that all available relevant data should be used. For specific classifications — e.g., the growth of a certain plant—a more restricted set of attributes may be required.

Table 3. Mean monthly attributes (measured over n years) used in the climatic classification of Australasia and southern Africa. (Russell and Moore 1976a).

Characteristic	Attribute
Temperature	Daily maximum temperature Daily minimum temperature Daily mean temperature Lowest temperature Absolute degrees of frost Daily temperature range
Rainfall and humidity	Rainfall Maximum rainfall in 24 hr Number of wet days Relative humidity at 0900 hr Relative humidity at 1500 hr
Evaporation	Free water evaporation
Daylength	Daylength
Derived ratios	Rainfall/evaporation $^{0.7}$ Rainfall/wet day
Integrated over time	Soil-water storage

Uses of Pattern Analysis Techniques

Classification of Climate

Williams (1976) has pointed out that there are a number of aspects to classification. Possibly the most important of these is purpose, and the main purpose of most classifications is prediction. From an agricultural point of view, a general-purpose climatic classification should be able to predict that certain plants will grow and that others will not. But special-purpose classifications may be required for more precise information.

Broad-scale classifications may be termed "general-purpose" and such classifications may be put to a variety of uses. Many of the classical classifications are of this type. However this generality is not essential, and for some purposes a specific classification may be adequate. Pattern analysis can be readily used for broad-scale classifications — e.g., the comparison of Australasia and southern-hemisphere Africa (Russell and Moore, 1976a). The overall pattern of climate groupings obtained in this classification was meaningful in relation to other information about vegetation and agriculture.

Pattern-analysis techniques can also be used to classify microclimates. Traditional climatic-classification methods are of much less value in these situations, yet, provided data is available, there is no reason why stable and useful microclimatic groupings cannot be obtained.

Detection of Homoclimates

The determination of areas of similar climate is of particular interest in plant geography and plant introduction. Comparisons of climates in different parts of the world have been carried out by various authors (e.g. Prescott 1938; Hartley 1960). Generally the term "homoclimate" refers to two or more stations with a similar climate, whereas the term "homoclime" refers to areas or regions that possess similar climates.

Studies of homoclimes have been carried out with reference to particular economic crops, *e.g.,guayule (Parthenium argentatum;* Prescott 1943), *Pinus radiata* (Prescott and Lane-Poole 1947), and the grape vine *(Vitis vinifera; Prescott.* 1965). Most of these studies involved comparison of various climatic attributes that were considered to be critical, such as amount or distribution of rainfall or temperature or simple ratios such as precipitation: evaporation. However, no attempt was made to express such similarities in a numerical form or to assess overall climate.

The development of computers and numerical methods enables greater quantities of data to be examined and a greater number of alternative hypotheses to be tested in the search for homoclimes. These developments also allow an agglomerative multivariate approach, as compared to the single-attribute or simple ratio-divisive approach used in the past.

The basic rationale behind the use of homoclimates in plant studies is that we are using climatic profiles of places (which are well defined numerically) on the earth's surface as a surrogate for climatic profiles of plants (which are not well defined). A climatic profile of a place consists of the values for a suite of climatic variables which reflect the climatic needs of the plant. The definition of climatic profiles of plants requires a much more detailed study over many environments and over a long period, and is influenced by differential tolerance of cultivars for climatic characteristics (e.g. frost tolerance, drought tolerance). The number of plants for which we possess this information is quite small. Some attempt has been made to produce itfor plantation crops, such as tea (Carr 1972). Much agroclimatological information has been collected about some of thetemperate cereals (e.g., Nuttonson 1957a, 1959b), but there is a lack of information about many of the tropical field crops.

Since so little quantitative information on climatic needs of cultivars and species of interest to us is available, it is necessary to make better use of the available climatic data. Thus — given an area where a particular cultivar grows well and which has a particular climatic profile — are there other areas in other parts of the world which have a similar climatic profile? This is known as analagous transfer of data (Nix 1968) and, theoretically, no knowledge of the plant involved is necessary at all.

One advantage of this approach is that a large amount of global climatic data is available. Wernstedt (1973), for example, has summarized monthly data on rainfall and temperature for 19 000 global stations. More detailed information on 11 monthly climatic attributes is available for 1740 global stations (Anonymous 1958). While inadequacies in data (quality, length of record, location, lack of detail, etc.) immediately become obvious when a study of a particular area begins, there is nevertheless an impressive amount of consolidated climatic data readily available, especially when compared with the lack of similar information on plants and soils.

There are several examples of the use of pattern analysis in the search for homoclimates. Two broad strategies are possible: a) given a region with a particular plant deficiency, what other areas in the world are similar and might be explored for suitable plants?, and b) given an area where a particular crop plant grows well, are there other areas that could grow this crop?

An example of the first strategy is in the search for suitable pasture legumes for the brigalow region of Eastern Australia (Coaldrake, 1970). Brigalow is a tree. *Acacia harpophylla,* that grows on clay soils in the semi-arid regions between latitude 28° and 18°S. After the forest vegetation is removed, crops and pastures grow well for a time, but the soil organic matter becomes depleted as cultivation intensity increases. There is a need in this region for the development of crop-pasture systems that can maintain soil fertility, but there is a lack of self-regenerating annual or perennial summer-growing pasture legumes that can be used in such pasture systems.

To obtain information on suitable homoclimates, Russell and Moore (1970) compared climatic data from 9 stations from the brigalow region with 139 selected global stations. In this analysis, Euclidean distance and Canberra metric with flexible sorting were used and there were 132 climatic attributes per station. Both summer (Oct to Mar) and winter (Apr to Sep) homoclimates were defined. As a result of the analysis, areas with similar climate in southern Africa (particularly Mozambiqueand Botswana) and in Argentina were identified. A recent plant-collecting expedition to South America included these areas of Argentina in the search for suitable legumes.

Examples of the second strategy are available from studies in Australia, which were undertaken to broaden the range of grain legumes grown. Grain legumes play a very minor role in Australian agriculture; less than 1.4% of the cultivated area is sown to them (Farrington 1974; Lawn and Russell 1978; Wood and Russell 1978). Grain legumes are seen as useful, both for their value as grain crops and as components of cropping systems with the ability to biologically fix nitrogen.

Climatic studies were undertaken to select areas in Australia similar to areas in Hokkaido, Japan, where the adzuki bean (*Vigna angularis*) is cultivated and to areas in India (Jain 1972) where black and green gram (*V. mungo* and *V. radiata)* will grow (Russell 1976).

In the case of adzuki bean, pattern analysis comparing 5 stations in Hokkaido with 45 Australian stations over the 5-month period May-September (Japan) and November-March (Australia) was carried out. In the case of black and green gram, 45 Indian stations were compared with 55 Australian stations over the 4-month period June-September (India) and December-March (Australia).

Sixteen monthly measured and derived attributes were used (Russell and Moore 1976a; Anonymous 1958). The Canberra metric and flexible sorting (Lance and Williams 1967) with $\beta = -0.25$ was used. The results of the analyses can be summarized by dendrograms indicating the similarity of the stations (Fig. 1, 2).

All five Hokkaido stations were associated in one grouping (Fig. 1). The most similar Australian stations were a group of nine high-latitude or high-altitude stations. When grown in Queensland, adzuki bean accessions of Japanese origin have been found to be sensitive to high soil- and air-temperatures, and homoclimates for these plants would appear to be in cooler areas or in the cooler parts of the growing season.

There was a clear separation between the Indian and Australian climatic stations for the summer period studied, with some exceptions (Fig. 2). Katherine grouped with the Indian stations Hyderabad, Bellary, and Sholapur at a low level. At a higher level 8 Australian stations — including Darwin and Queensland tropical-coast locations from Thursday Island to Mackay — grouped with 19 Indian stations (mostly coastal). Bangalore, a moderate altitude station, grouped at a low level with Herberton.

With these exceptions, the analysis was not particularly useful from the point of view of predicting homoclimates for black and green gram. However this may have been partly due to the lack of definition of type localities for black and green gram. Restricting comparisons to a few well-defined type localities and a large number of other stations may be the most useful approach.

Grouping of Experimental Areas and Locations

Frequently, information on the same plant is

Figure 1. Dendrogram showing relationship between summer climate recorded at Hokkaido, Japan, and at Australian stations.

available for a number of different stations. Pattern analysis can be used to climatically group the stations with similar environments. There are a large number of research stations in Australia, working with wheat extending over a distance of 3000 kilometers and a latitudinal range of 18°. Using climatic data related to the phasic development of the wheat variety Gabo, Nix (1975) was able to dividethe wheat-growing areas into agroclimatic zones. He was also able to show that wheat-variety recommendations that had become established through many years of trial-and-error experimentation corresponded to these zones defined by pattern analysis. He was also ableto suggest changes in plant-breeding strategies based on the analysis.

Geographic Extrapolation of Experimental Results

One of the limitations of agricultural experimentation is that it is undertaken at specific locations. Although attempts are made to carry out research at other locations, it is never possible to increase the sites to the range of environments that should be covered.

One approach is to determine the similarity of other stations to the experiment station. This approach is currently being used in CSIRO's Division of Tropical Crops and Pastures. This Division has widely separated research stations located within 15° and 27° of latitude. The application of results from these stations is greatest in areas with similar climate. Hence isoclimes of areas of similar climate are being determined both in Australia and overseas, allowing more precise transfer of information. Such an approach could also be a worthwhile exercise for the international agricultural research institutes.

Domain Definition

The use of pattern analysis in domain-definition has been discussed by Austin (1971). This approach has been used in ecological studies, but

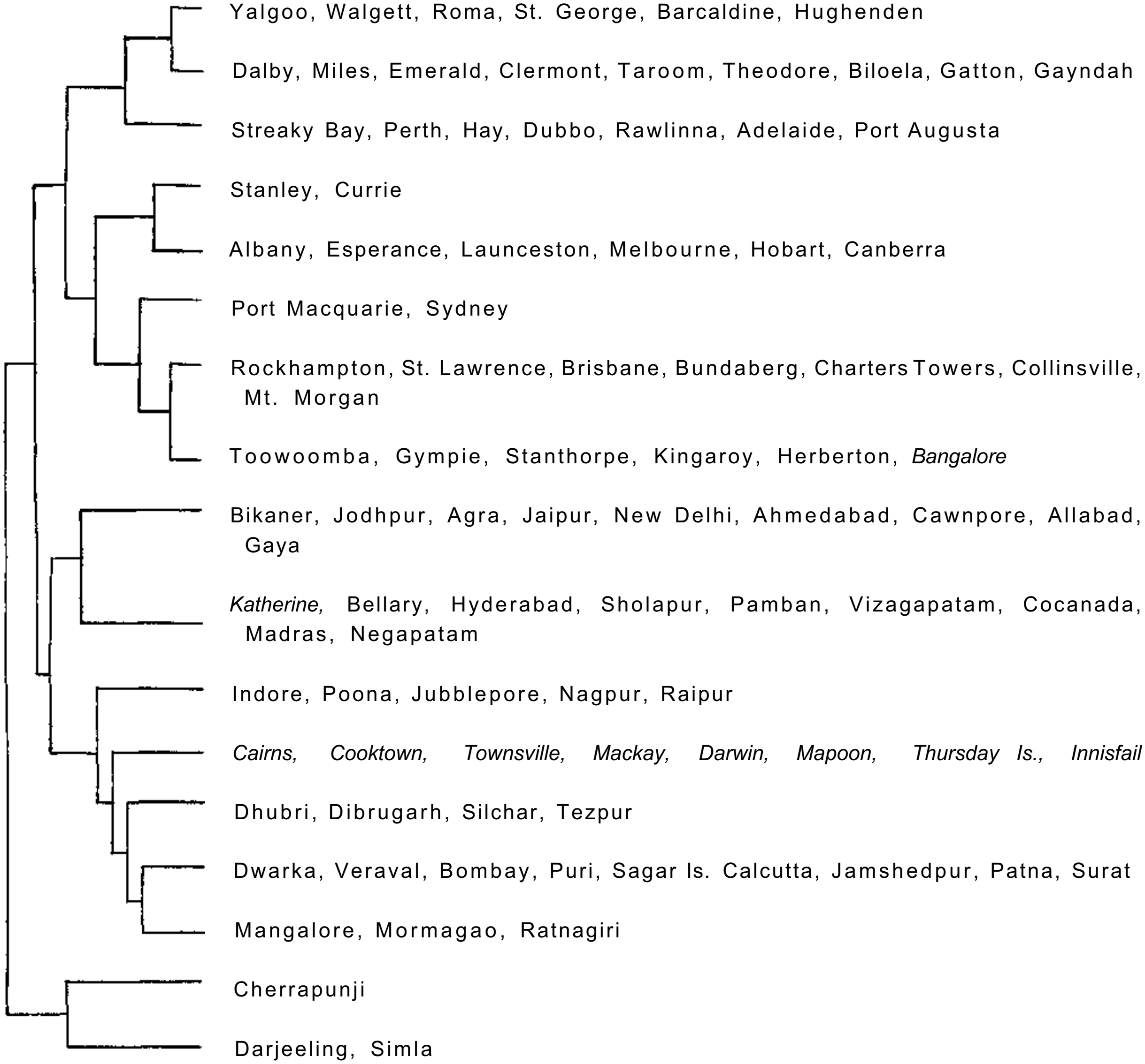

Figure 2. Dendrogram showing relationship between summer climate recorded at Indian and at Australian stations.

it has a potential value in agriculture. Domain definition refers to the selection of areas of reasonably homogeneous climate. Within such areas, more refined analyses (such as regression analyses) can then be applied. This approach has possible application in the analysis of widely distributed common field experiments.

Conclusions

Pattern analysis is an approach with considerable potential in agricultural experimentation, in the classification of climate, and in defining climate-plant relationships more precisely.

There are a number of limitations to the wider use of the approach. Firstly, access to computing facilities of reasonable speed and capacity is essential. This is less of a problem than it used to be, but asthe number of stations and number of attributes in some analyses increase, the computing requirements can quickly saturate even the largest and fastest computers. Williams (1976) has given some information on the relationship between numbers of stations, attributes and numerical method, and computing-time requirements. For certain similarity analyses, computing requirements increase as n^2 where n is the number of stations being compared. Once n exceeds 300, the time requirement (and cost) escalates rapidly. Secondly, the choice of attributes used in the analysis requires further research. In many cases, of course, the data available is so limited that all of it has to be used. Nevertheless situations do arise where a large number of attributes are available and some selection is desirable. At the moment this is not carried out on a systematic basis. Thirdly, a most important limitation to the application of pattern analysis in many climatic studies is the lack of consolidated data in areas where comparisons are needed. There is no short-term solution to this problem, but there has been a gradual increase in the amount and quality of climatic data available. Further enhancement of the amount, distribution, and quality of data should be an international objective.

The numerical methods used in pattern analysis are still evolving. During the past 15 years there has been a large increase in the number of papers published in this area, and computer packages are readily available. The main challenge to research is at the climate-plant interface, and much better definition is required at this level.

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The Development of Agrometeorology in Upper Volta: A Brief Note

Frederic Niama Ouattara*

Summary

Upper Volta has a network of 300 rainfall, 16 climatic-observation, 9 agrometeorological, and 7 synoptic stations. The agrometeorological service was created in 1976 and is being strengthened. In this paper an organizational chart of the meteorological services in Upper Volta, position of the Intertropical Front in West Africa at different times of the year, and maps showing isolines of the mean and dependable amounts of rainfall at 25 and 75% probability levels for annual precipitation and the month of August precipitation are included. Future lines of work for improving the agrometeorological service are indicated.

Upper Volta

Located in the heart of West Africa, with a surface area of 274 000 km^2, Upper Volta extends from 10° to 15°N latitude and from 05°W to 02°E longitude.

The climate of Upper Volta is controlled by the predominance of two airflows: (1) a northeast to east flow of dry air originating from high Saharian pressures, hot during the day and cool at night due to the considerable ground radiation, or (2) a southwest to south flow of humid air (the West African monsoon) originating from high austral ocean pressures in which the rainy-season clouds and tropical disturbances form.

The separation zone between these two flows fluctuates between the southern side (around January) and the 25th parallel (towards August) in such a way that the passage from one flow to the other first occurs between April 15 and May 15, depending on the region (change from a dry continental air flow to a humid air flow) and changes again between the first and 30th of October (from a humid air flow to the dry continental air flow).

The part of the country located to the south of the 14th parallel is allied with the Sudanic climate zone, whereas the extreme north — with its intense evaporation, low humidity, major diurnal differences in temperature (15° to 20°C) and its rains — exhibits characteristics close to those of the Saharan climate zone (Fig. 1).

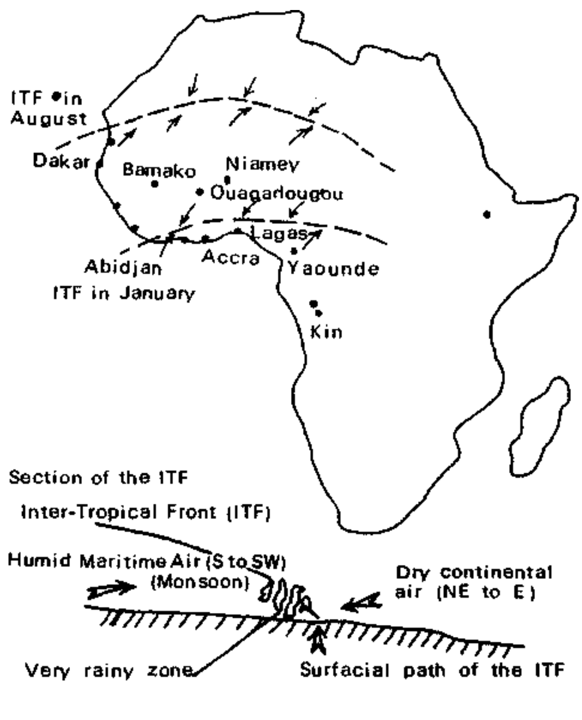

Figure 1. Position of the ITF in West Africa.

The principal soil types are:

- Subarid, tropical, *cambiques* soils
- Ferruginous, tropical soils (Luvisols and Acrisols)
- Ferrallitic soils (Nitosols and Ferralsols)

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Vertisols and eutrophic brown soils are sometimes found.

Upper Vofta's Meteorological Service

The meteorological structure that has existed in Francophone West Africa since 1960 was established for the correct operation of civil aviation in these countries, but not intended to be used for agriculture. In Upper Volta, this has resulted in the creation of a substructure for agricultural meteorology, within a national meteorological service. The national meteorological service, (Fig. 2) has accorded an important place to agrometeorology since 1976.

The meteorological system (Fig. 3) includes:

- 300 rainfall posts,
- 16 climatic stations,
- 9 agrometeorological stations,
- 7 synoptic stations.

The rainfall readings are transmitted every day by the administrative command network (Reseau Administratif de Commandement, or RAC). The climatic and agrometeorological stations transmit their observations by mail.

At present only the seven synoptic stations transmit their observation by BLU transmit-receiver sets. An extension of these BLU sets to five subsequent stations is foreseen. An APT apparatus (Automatic Picture Transmission) is also planned to receive meteorological satellite photos, which would provide knowledge of the cloud cover. In furtherance of this idea we have entered into close collaboration with the regional teledetection center in Ouagadougou. Actually, the regional teledetection center is designed to receive, process, and diffuse satellite information for a large number of African countries for whose coverage it is responsible.

Measurements Undertaken by the Meteorological Service

Numerous atmospheric parameters are regularly observed in the context of the meteorological system; for example:

screened temperature at the soil surface and in the soil;

wind velocity 2 m above the soil and at a high altitude;

soil pressure;

air humidity and soil humidity;

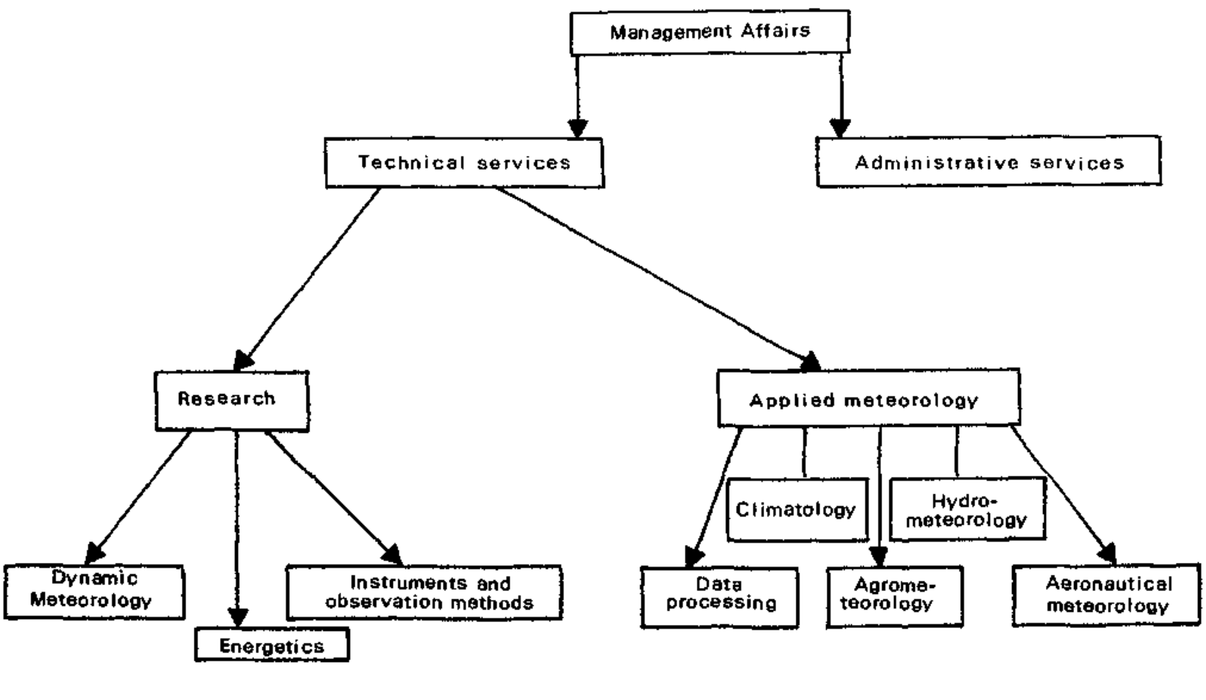

Figure 2. Organization Chart of the Meteorological Service in Upper Volta.

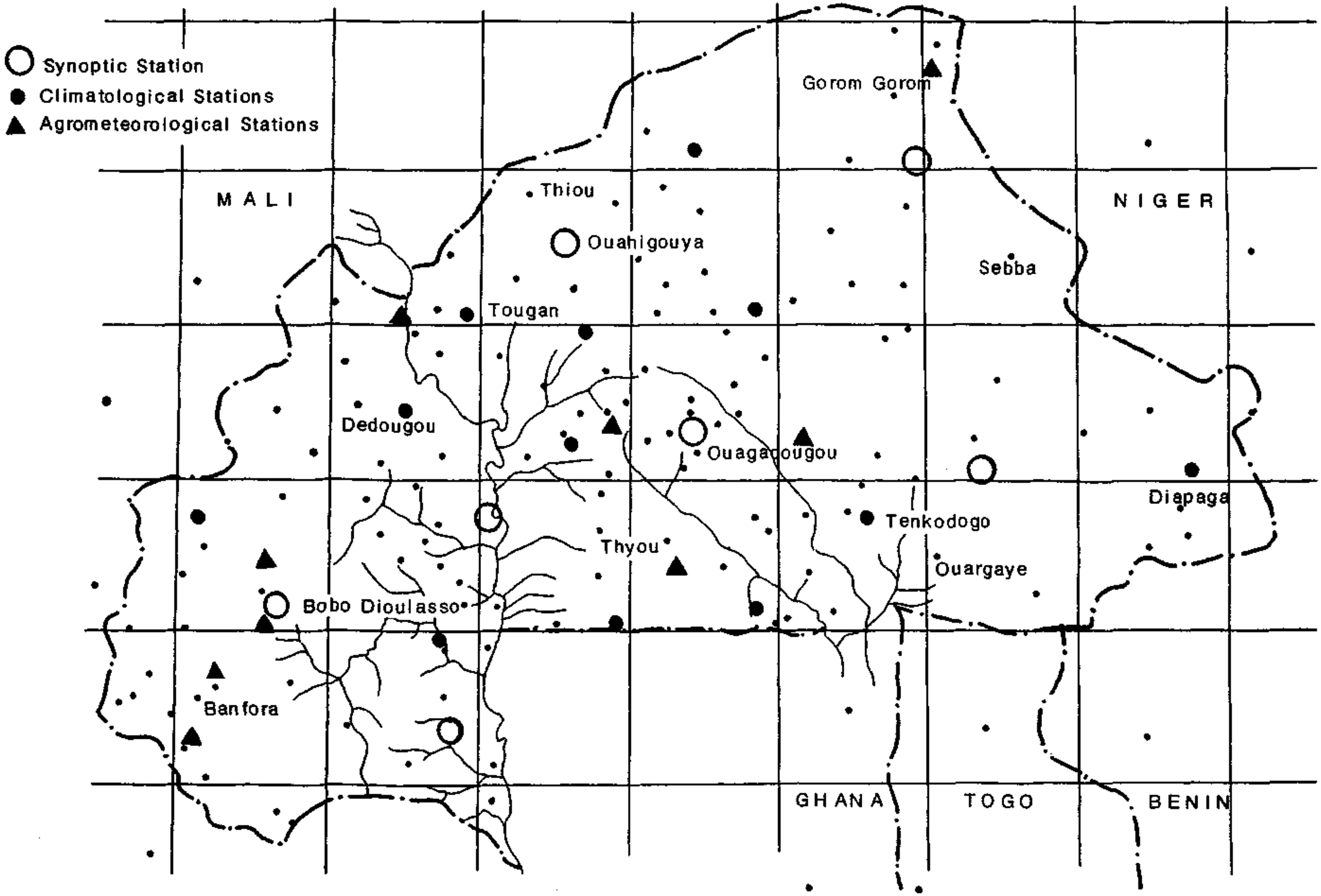

Figure 3. Location of synoptic, climatological, and agroclimatological stations in Upper Volta. (Source: Upper Volta Meteorological Service, 1 Jan 1976)

- precipitation (pluviometer, recording rain-gauge)
- global radiation and the duration of sunlight (pyranometer and the heliograph);
- evaporation (Class A pan, *piche,* Colorado pan).

Special measurements such as runoff and evaporation are made at some agrometeorological stations.

1. Phenological observations pose a major problem due to the lack of observers in this area. A simplified manual for the use of volunteer observers in this area is being produced.
2. The data thus collected for the network as a whole are sent to the Office of Meteorology, where they are checked, analyzed, and manually transcribed into documents that can be easily and accessibly stored, such as file cards. The registration and storage of data on magnetic tapes and records is foreseen as soon as the computer plannedfortheAgrhymet Regional Project for the Sahel countries is installed.

Already Completed Studies

Numerous studies have already been carried out by the meteorological service of Upper Volta; those that assist the agricultural services are:

AGROMETEOROLOGICAL STUDY OF THE BOBO-DIOULASSO REGION. The Bobo-Dioulasso region constitutes the southwest part of the country and is known for its economic activity. The goal of the study was to show potential users of agrometeorological information the variability of climatic parameters (by location) and the frequency at which certain thresholds are attained, which made it possible to recommend for or against some techniques or crops at a given period.

SOLAR ENERGY AND DURATION OF INSOLATION IN UPPER VOLTA. The study of solar energy has made it possible to determine the levels of solar energy available for the whole country. This has been helpful in determining (a) possible exploitation of the water table for irrigation with solar pumps and (b) the feasibility of using solar ovens and stoves to avoid deforestation. The average annual global radiation value is 500 cal/cm^2 per day for the entire country.

PET AND ITS DETERMINATION BY THE PENMAN METHOD OF ENERGY BALANCE. This document is widely used by irrigators and constructors of water reservoirs.

FREQUENCY STUDY OF ANNUAL AND MONTHLY RAINS. The goal of this study was to complete the average isohyet maps for 1/4, 1/2 (mean), and 3/4 frequencies of the rains, for one year in four, one year in two, and three years in four, respectively (Figs. 4, 5, and 6). Similar data for August are presented in Figs. 7, 8, and 9.

ESTABLISHMENT OF RAINFALL PATTERN. This study has permitted a region-by-region determination of the dates when seeding has reasonable chances of success. With one year calculated, it is possible to determine the probable success of the farmers' seeding at the start of the rains, taking into accountthe nature of the soil and the preparatory tilling.

MONTHLY AGROMETEOROLOGICAL BUL'LETIN. This is put out during the rainy season which, in particular, gives the rainfall and potential evapotranspiration distribution for the entire territory.

Many other technical documents have been prepared by the agrometeorological service in response to some of their clients' needs.

In the area of yield forecasts, however, everything still remains to be done, as any progress on this plan has been hampered by the lack of valid statistical yield data. All these aspects will befollowed up as soon as possible because the agrometeorological service presently has access to a large plot of land in the middle of the national meteorological center of Ouagadougou, which is located at the entrance to the city. This land will be used for different experiments, especially to illustrate certain agricultural production ideas in relation to the climate.

To summarize, the agrometeorological service is already off to a good start in Upper Volta; however, it will not be ableto fully respond to its objectives until:

- the service is well structured, with adequate staff and material;

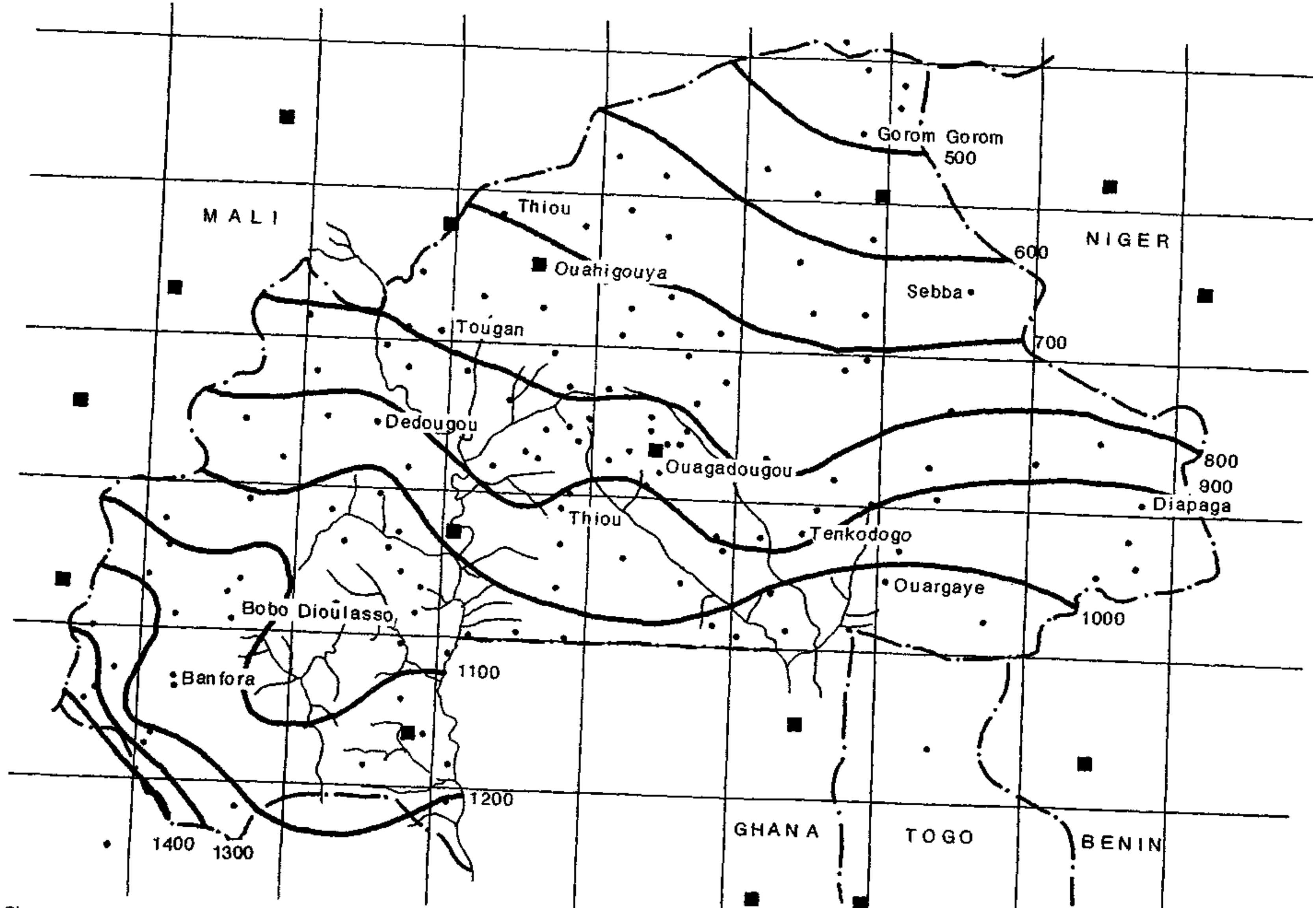

Figure 4. Isohyets of the mean annual rainfall (mm). (Source: Upper Volta Meteorological Service, 1 Jan 1976).

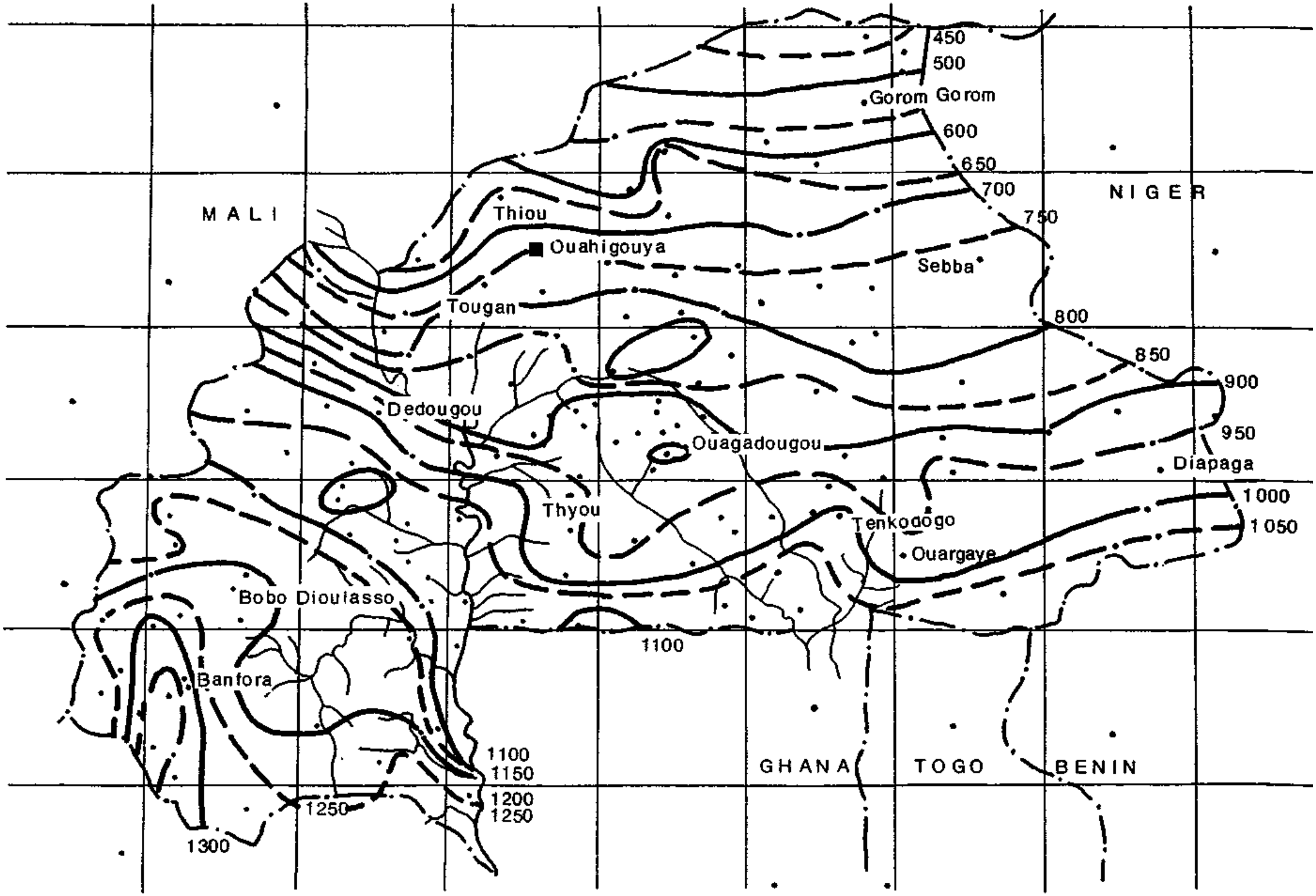

Figure 5. Amount of annual rainfall (mm) at 25% probability. (Source: Upper Volta Meteorological Service, 1 Jan 1976).

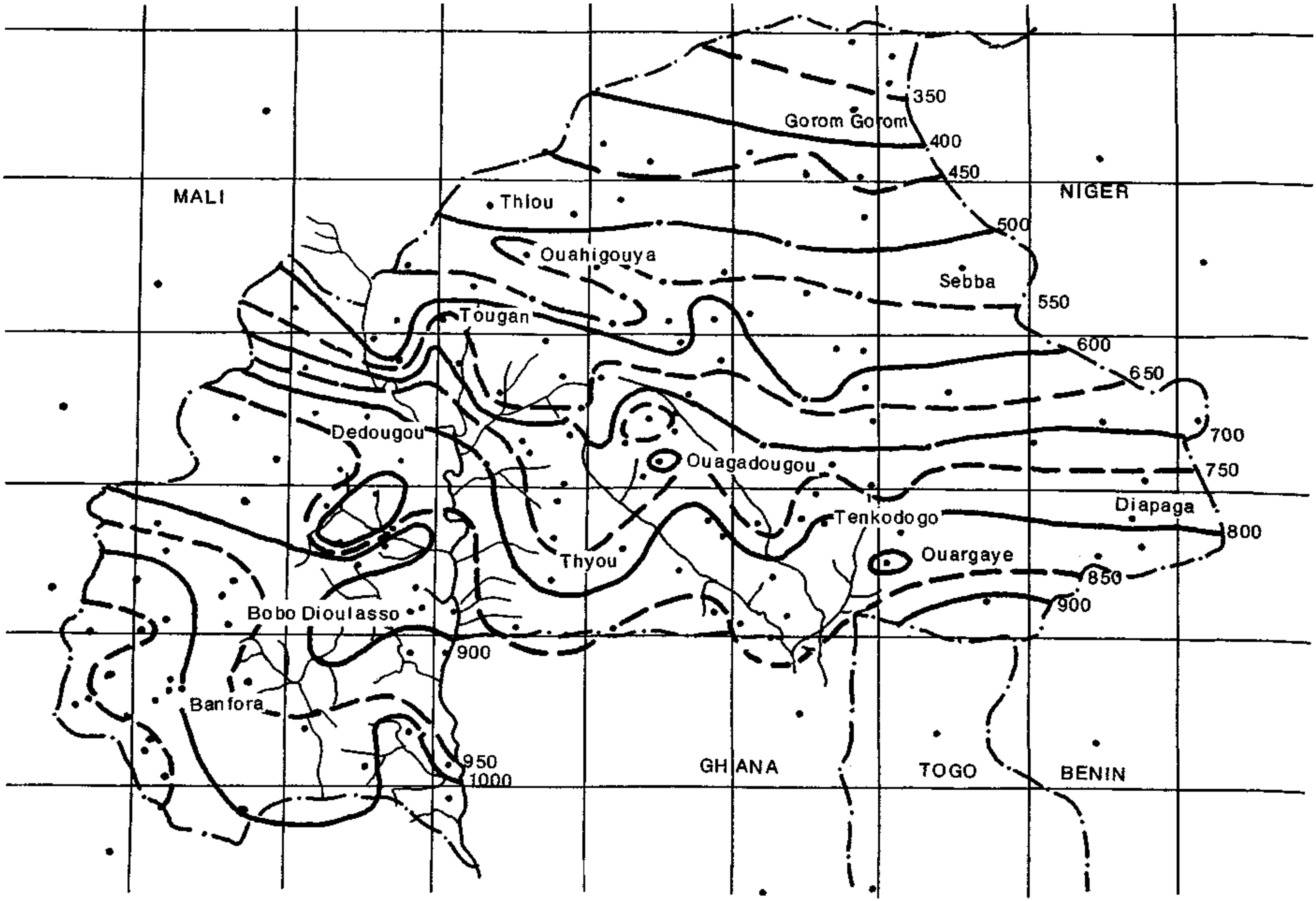

Figure 6. Amount of annual rainfall (mm) at 75% probability. (Source: Upper Volta Meteorological Service, 1 Jan 1976).

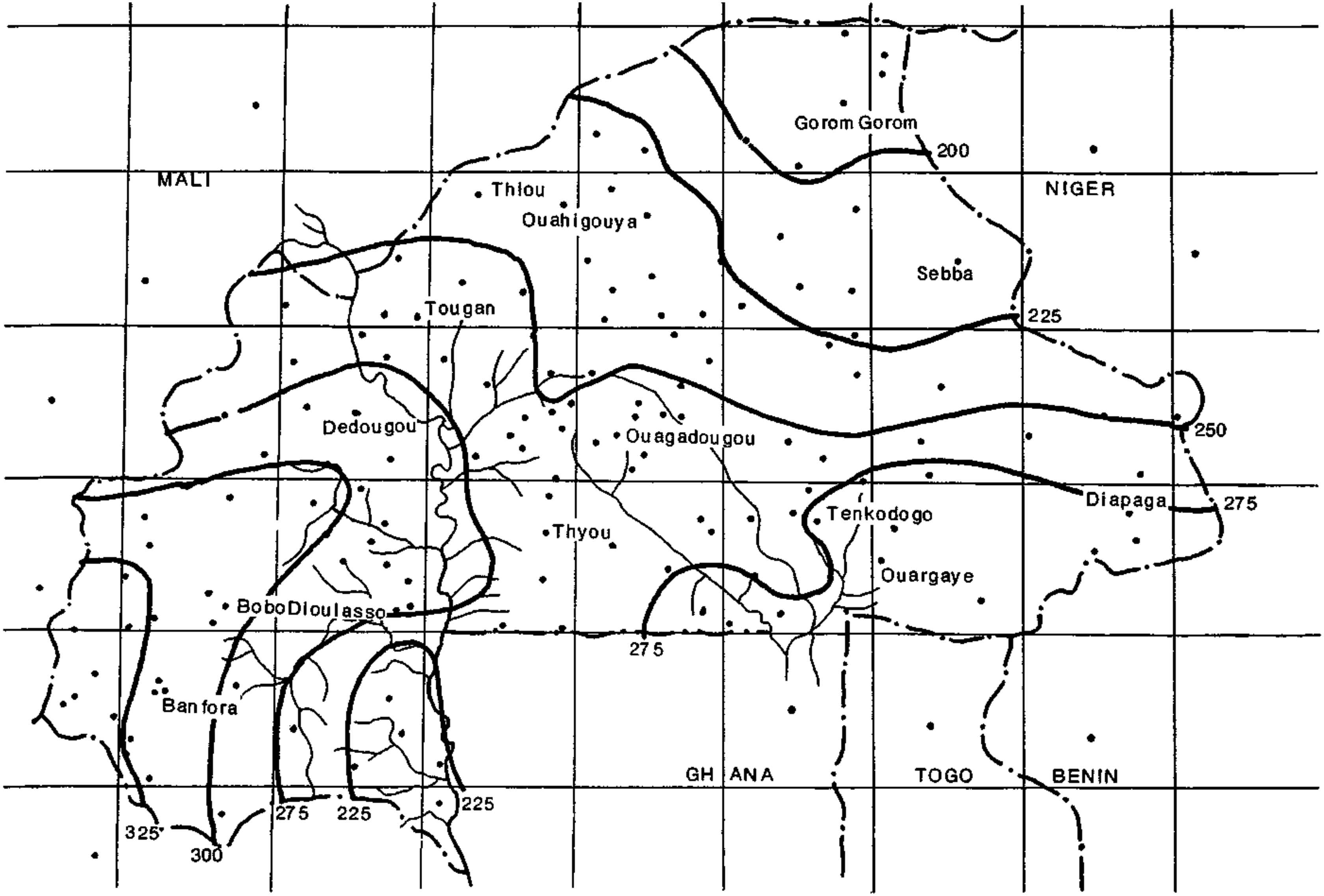

Figure 7. Isohyets of the mean rainfall (mm) in August. (Source: Upper Volta Meteorological Service, 1 Jan 1976).

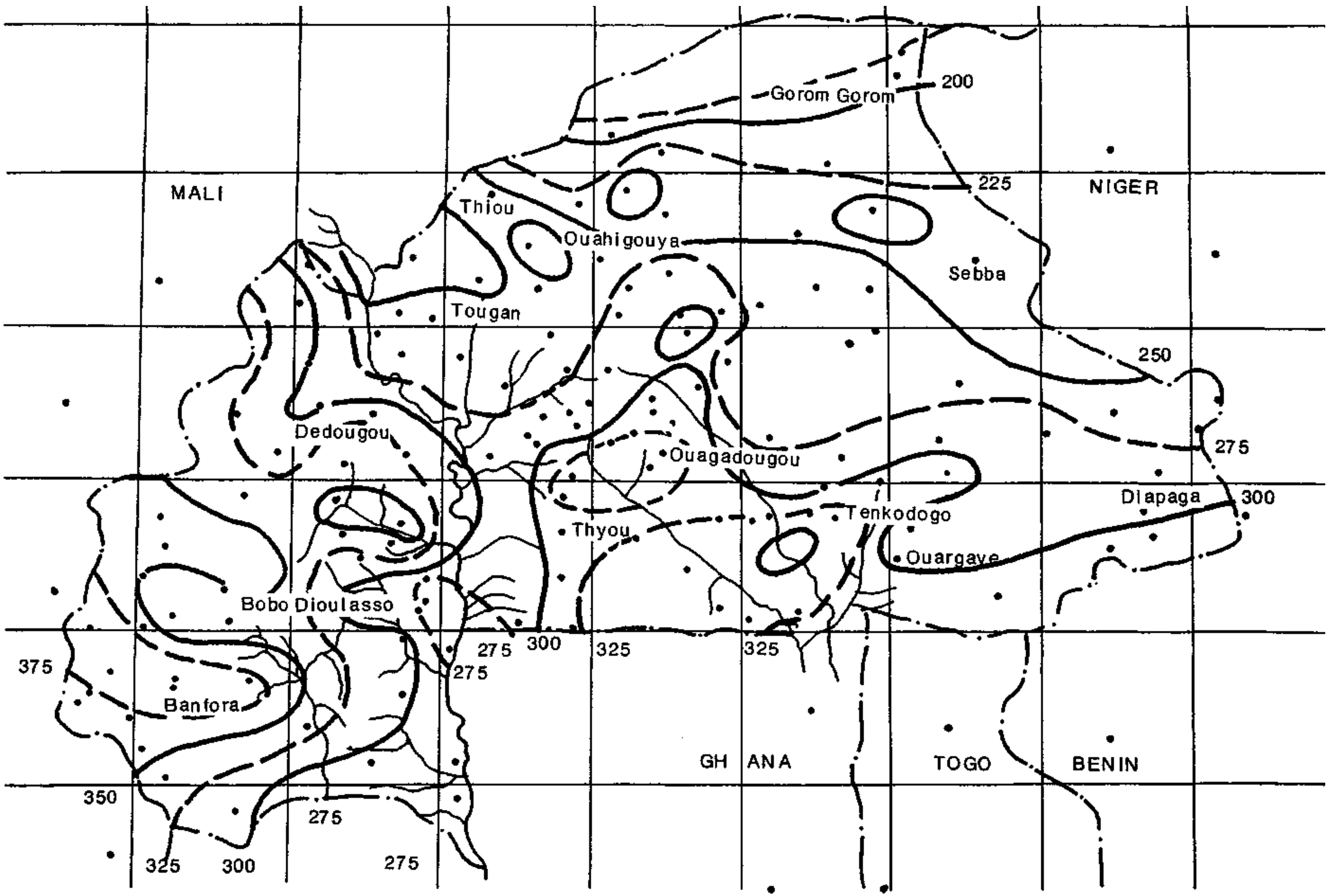

Figure 8. Amount of August rainfall (mm) at 25% probability. (Source: Upper Volta Meteorological Service, 1 Jan 1976).

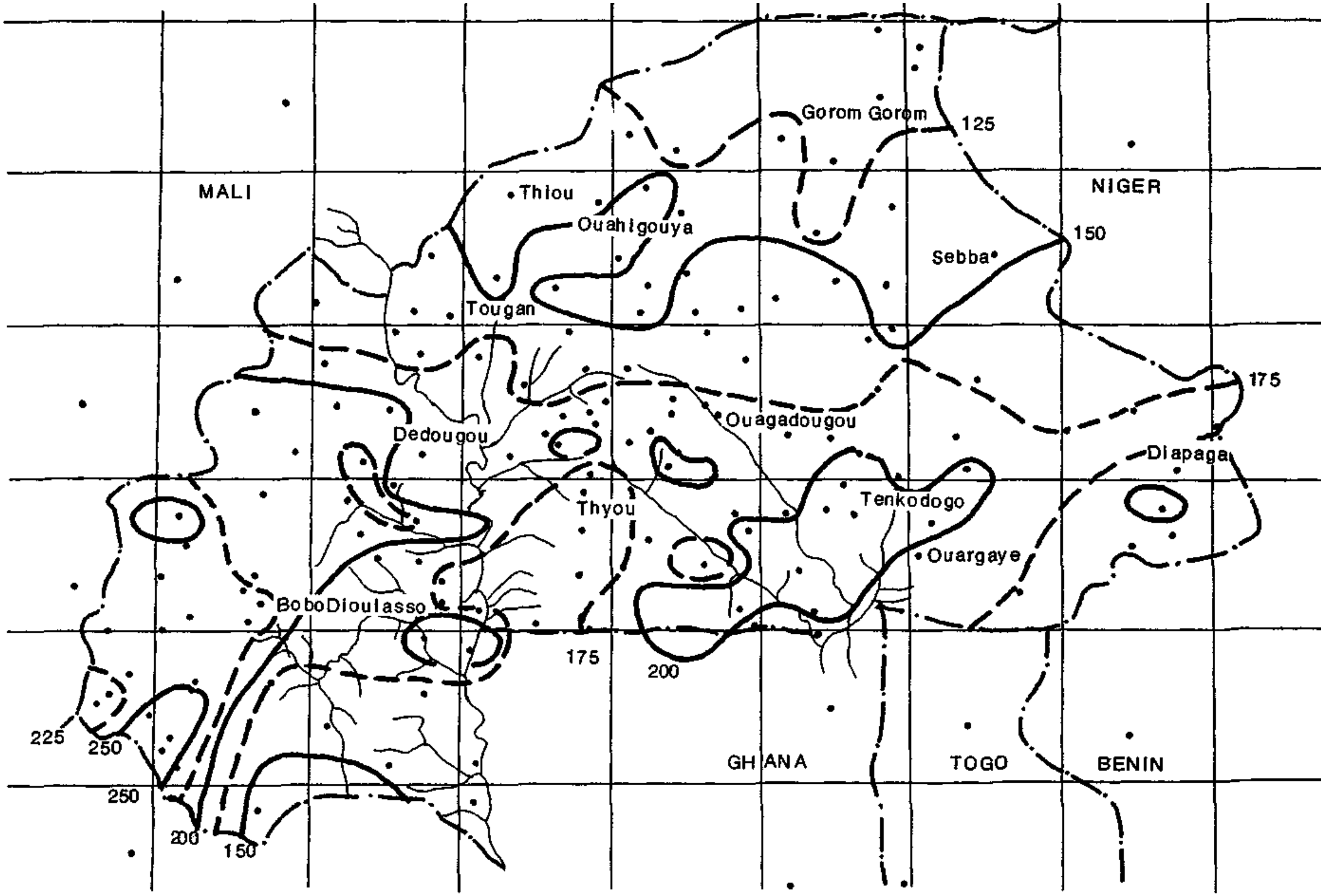

Figure 9. Amount of August rainfall (mm) at 75% probability. (Source: Upper Volta Meteorological Service, 1 Jan 1976).

- the means of rapid transmission are functional;
- calculation resources are developed that will permit major statistical calculations to be made (correlations from forecasts of the monthly water balance by introducing conditional probabilities in the determination models of this parameter, etc.).
- the level of meteorological forecasts is improved. In this area we place much hope in the teledetection center in Ouagadougou, which will assure the reception and treatment of satellite photos.

We have just given a quick sketch of the agrometeorological service in Upper Volta. We would be happy to have any suggestions or recommendations towards the continuation or modification of some aspects of the work undertaken in this area.

Session 2

Water-budgeting Models and Their Application

Chairman: R. H. Shaw
Co-chairman: R. P. Sarker

Rapporteur: A. K. S. Huda

Summary and Recommendations

This session covered a range of topics. A basic paper on modeling evapotranspiration (King) summarized a number of the equations used to estimate evapotranspiration. One might question the complexity of some of these, but it should be recognized that they are used to explain the basic evapotranspiration process and the factors involved, a procedure that requires physically sound models, which may be estimated with greater accuracy than is required for many application problems. However, these approaches are important and may provide clues as to what changes might be made in management by knowing exactly what factor caused the evapotranspiration. For example, a study of canopy resistances under various management systems might provide information on changes that could be made to conserve water. Some of this type of work needs to be done with this viewpoint in mind.

Individuals and groups working on these problems should all understand these models (at least what they do) and the assumptions involved. This seems a necessary component of future training.

Various aspects of the water budgeting procedure were discussed. The versatile soil moisture budget as presented by Baier is one possible model that could be tested. It seems advisable that ICRISAT collect the data to test a number of models, to evaluate, and to develop if necessary, models that will give adequate estimates. It is doubtful if any one model will prove to be the best everywhere under the wide range of weather conditions that occur. By developing such models, soil moisturedata can be estimated for situations or areas not actually measured. This should be possible once a satisfactory model is available. This seems of primary importance in the SAT, where water supply is a major problem. At the same time, steps should be taken to collect the agrometeorological data necessary for this, and other purposes.

Dr. Russell spoke on the dynamics of soil moisture in Vertisols and Alfisols. Work needs to be continued to develop a thorough understanding of the soil moisture characteristics of the tropical soils. Several speakers presented data showing soil moisture profiles; such data should be collected at many sites under different cropping conditions to determine: where is the water in the profile; when is it there; and how much is present. These questions must be answered if the water balance and its effect on agriculture are to be measured.

Franquin pointed out that water-balance programs should involve minimum cost. It is important that costs be considered with approaches used which will provide the desired accuracy for the particular problem without overmeasuring certain parameters. Franquin presented a water-balance model (stochastic model) and showed how it could be used to determine subhumid and humid periods. This kind of procedure might be very useful as part of an agrometeorological climate-typing system.

Dancette's paper concentrated on the water requirements of millet, but other crops were freely discussed. Varieties within a crop showed different water use, and therefore different adaptations to the cropping systems. Such data should be obtained for more areas and for more crops, to obtain information on how best to utilize available water and find the most efficient cropping systems, including intercropping. However, water use is only one part of the intercropping problem. Radiation measurements are an essential part of this program.

The final paper by Ryan reported on another aspect of the water balance — runoff. In addition to empirical models, further measured data may be necessary. The most efficient size system needs to be examined for all areas of the SAT where tanks may be installed as part of the farming system. Franquin mentioned one point that seems to have received little emphasis so far — excess water can be as damaging as lack of water. This factor needs to be considered in future programs.

Recommendations

1. Recommendations Nos. 2 and 3 from Session 1, that the specific data requirements for agrometeorological data be outlined and that an effective system be developed,

can again be seconded. The observations necessary for water-budgeting models need to be included.

2. Various water-budgeting models should be evaluated for the crops grown in the SAT and tested over the SAT area. This requires measuring the different components of the water budget.
3. Data should be collected on soil moisture to show where in the profile water is present, when it is present, and how much is present.
4. The water requirement of different crops and varieties grown in the SAT should be evaluated.

Profile Moisture Dynamics of Soil in Vertisols and Alfisols

M. B. Russell*

Summary

Research to develop and evaluate alternative systems of soil and crop management for increasing and stabilizing food production in the SAT should give particular attention to the dynamics of water as it moves into and through the soil-plant-atmosphere continuum. More complete understanding of the physical processes which determine such dynamic behavior and of the natural and man-induced factors that control them will provide an improved basis for interpreting system performance and for generalizing the results of site- and season-specific field experiments on various production practices.

Water management in the rainfed areas of the semi-arid tropics is basically a problem of using as fully as possible the erratic seasonal rainfall to meet the transpiration needs of crops. The soil profile serves as a means of balancing, over time, the discontinuous water supply with the continuous atmospheric evaporative demand. Consequently, the physical capacity of the soil for water storage and the rates at which water can move into, out of, and within it have important effects on both the short-term and the seasonal dynamics of the hydrologic cycle. The properties of the soil profile obviously affect its moisture retention, runoff, and drainage as well as the losses of water by evaporation and transpiration. This paper discusses work being done 1) to quantify the dynamics of water in the Alfisols and Vertisols at ICRISAT Center, and 2) to relate such measurements to crop growth.

The physical capacity of the soil profile for water retention is determined by its depth and porosity. Because our primary interest is ultimately on water use by crops, we use final rooting depth as the basis for establishing profile depth. In the deep Vertisols this is taken as 187 cm. Drainage is therefore defined as the downward water flow across the 187-cm plane and profile-water storage is the measured water content in the 0- to 187-cm section. For medium-deep Vertisols, we use either 127 or 157 cm as the effective profile depths, and for the Alfisols we use 127 cm.

Profile porosity is determined by measuring bulk density on carefully taken soil cores or, in the case of stony horizons, large soil blocks of known volume. The Vertisol profiles are physically quite homogeneous and isotropic. The bulk density of the upper 20-cm layer varies with tillage and seasonal drying and averages 1.3 g/cm^3. Below that depth it ranges between 1.35 and 1.45, with an average of 1.4 g/cm^3. These values give a total water-retention capacity of 880 mm for the 187-cm deep-Vertisol profile and 710 mm for the profile depth of 157-cm in the medium-deep Vertisols.

The Alfisol profiles are much more heterogeneous, with marked vatiation in clay content and stones at different depths. Since these properties vary greatly with depth and over short horizontal distances, it is difficult to make meaningful generalizations concerning the water-retention capacity of Alfisols. Bulk densities commonly range from 1.5 to 1.95 g/cm^3 and the percentage of particles >2.0 mm from 0 to 70%. It is therefore necessary to measure both of these quantities at several points in each of the areas being studied to arrive at the site-specific profile-storage capacities for use in quantitative water-balance and crop-water-use studies.

The time and depth changes in profile water content below 22 cm are measured by neutron

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moderation. Changes of water content of the upper 22 cm are measured by composited gravimetric samples taken manually with sampling tubes. Time and depth changes in hydraulic head are measured with tensiometers. These are used to follow the time and depth patterns of the onset of stress in the root zone and to indicate the size and direction of the vertical hydraulic gradients within the profile, especially across its lower boundary.

The plant-available water capacity of the soil profile is determined from field measurements. The upper limit is defined as the amount of water retained by an uncropped profile following cessation of drainage after infiltration of water in excess of that required to fully recharge it. Loss by evaporation during the drainage period is usually minimal, but it can be suppressed, corrected for, or ignored. For the deep Vertisols, the average field capacity of the 187-cm profile is about 815 mm.

The lower limit of plant-available water of the profile is also operationally defined as the minimum water content throughout the profile as measured in the field under a well-managed deep-rooted long-season crop grown in the postrainy season. We have found that residual-moisture profiles in the deep Vertisol at harvest of good postrainy season crops are quite similar; hence, we are using the minimum values so obtained as the de *facto* lower limit of plant-available water. For the deep Vertisol this is 590 mm. Not included in this estimation is the amount of water below the 15-bar percentage lost from the upper 45 cm of the profile, because evaporation can reduce the moisture content below the 15-bar limit to this depth.

The distribution in layers of plant-extractable water in four profiles is shown in Figure 1.

The various soil-profile layers undergo periodic accretion and depletion of water. The amplitude and periodicity of these cyclic changes are determined by the capacity of the layers and their position in the profile, as well as by the amount and frequency of the water additions and withdrawals. The seasonal recharge of the uncropped deep Vertisol in 1977 and its subsequent depletion in the 6-month postrainy period and plotted in Figure 2.

Changes in hydraulic head in the fallow Vertisol profile during the 1977-1978 postrainy season are plotted in Figure 3. The curves clearly show the change from downward to upward water-moving gradients in the upper part of the profile as evaporation gradually replaced drainage as the mechanism causing the slow decline in profile-water content.

Loss of water by evaporation from the soil surface is a major component of the annual water balance under SAT conditions. The magnitude of such losses shows large year-to-year and site-to-site variations, depending on the frequency of rains and the density and longevity of the vegetative canopy. When the soil surface is wet, evaporation occurs at a rate controlled by energy supply and atmospheric demand conditions. As the soil surface dries, the rate of evaporation decreases with time. This is caused by the inability of the unsaturated sub-surface soil to transmit water to the site of evaporation at or just below the soil surface at a rate sufficient to meet the evaporative-loss rate; hence there is a net loss of water from the soil-surface layer, which further reduces the subsurface supply rate.

If the surface soil is recharged by rain or irrigation, the evaporative-loss rate again returns to that determined by atmospheric demand, as indicated by the open-pan evaporation rate. The loss rate from the soil surface also will be reduced, irrespective of the moisture conditions of the surface if radiant energy reaching the surface is reduced. Such reduction occurs on cropped land as a result of the interception of incoming solar radiation by the crop canopy.

It is clear, therefore, that under conditions of Inermittent rain the amount of water lost from cropped land will be a highly dynamic factor affecting the overall efficiency of water use. Field studies of the short-term variations of soil moisture in the upper part of the soil profile during the early part of the growing season have been conducted to test a simple predictive model of evaporative loss. Agreement between the predicted available water in the upper soil layers with that measured by gravimetric samples taken in the field was satisfactory.

The daily evaporative loss, E, is estimated as a function of the open-pan evaporation rate, E_p; the number of days, t, following a rain of sufficient size to recharge the surface 10 cm of soil; and the fraction, β, of incoming solar radiation reaching the soil surface. The equation $E = \beta\ (Ep/t)$ is used to compute the daily evaporative loss from the daily rainfall and

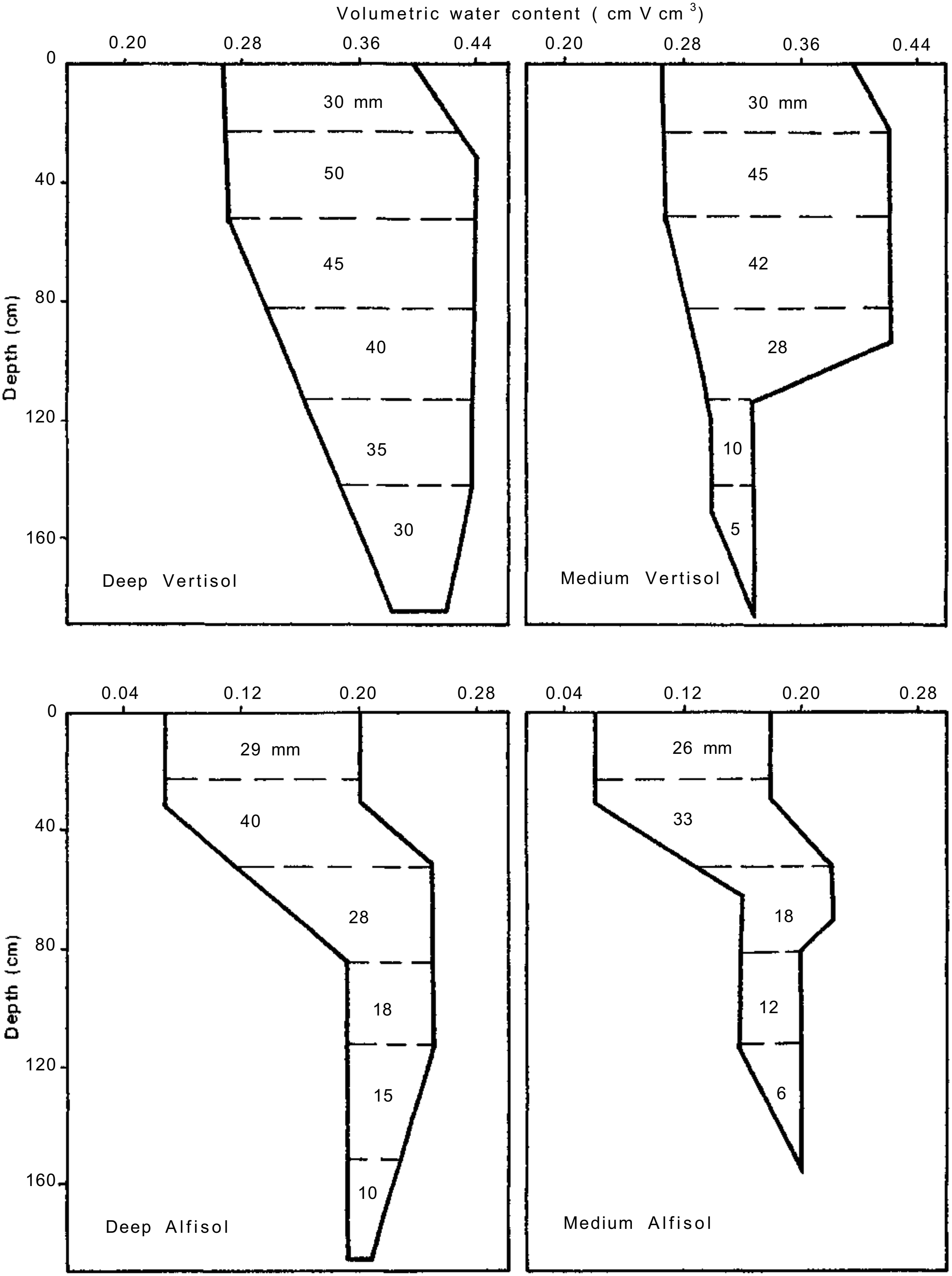

Figure 1. Available water profiles for four soils.

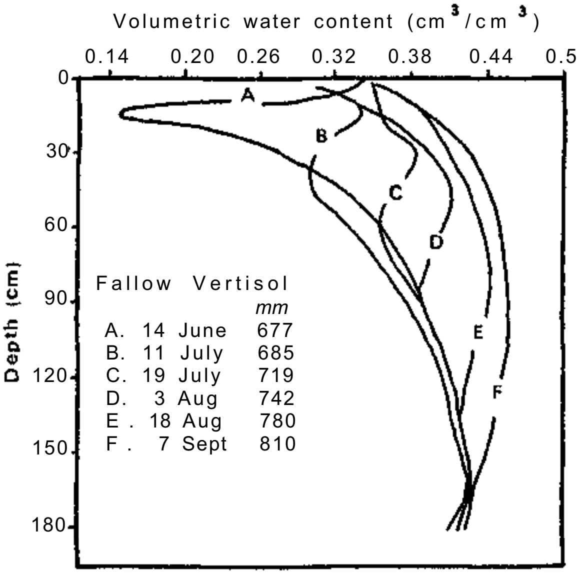

Figure 2a. Moisture profiles of an uncropped deep Vertisol during the rainy season.

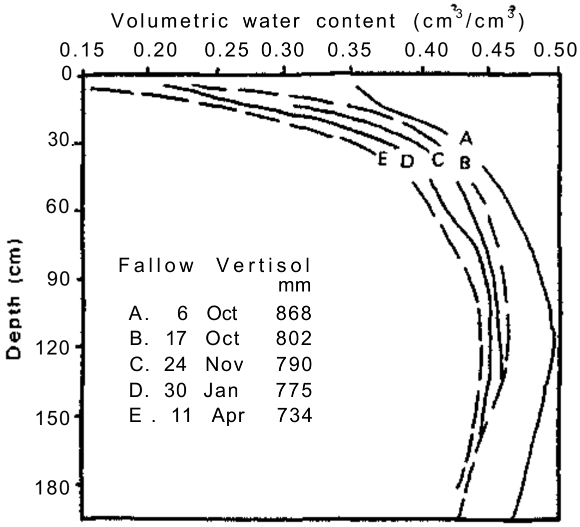

Figure 2b. Moisture profiles of an uncropped deep Vertisol during the postrainy season.

open-pan data. Under uncropped conditions β = 1.0, but under a crop it is a time-dependent function of crop growth that can be measured directly or estimated from the LAI.

The time and depth changes in profile-water content are being used to follow the seasonal changes in drainage, evaporation, available

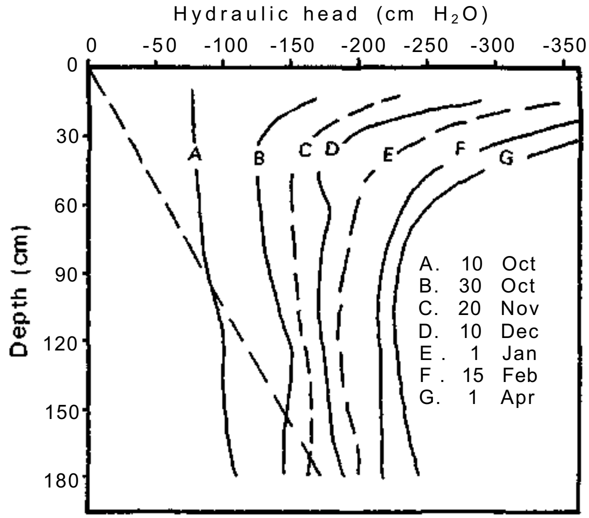

Figure 3. Hydraulic-head profiles in an uncropped deep Vertisol during a drying cycle.

profile moisture, and transpiration during the rainy and postrainy seasons on the Vertisols and Alfisols at ICRISAT Center. Illustrative examples of such time and depth changes are plotted in Figures 4 and 5.

Using measured values for daily rainfall (P), irrigation (I), open-pan evaporation (E_p), runoff (R), fractional radiation at the soil surface (/i), and change in profile-water content (A M), it is possible to quantify the water-balance equation: i.e., $P + I = \Delta M + R + D + E + T_m$. The drainage term is based on the profile-storage capacity and transpiration (T_m) is obtained as the residual in the equation. Another estimate of transpiration (T_e) also is computed as $T_e = E_p(1-\beta)$. This assumes no advection and no water stress. A set of water-balance equations fora postrainy-season sorghum crop on a deep Vertisol is presented in Table 1. Seasonal water-balance equations for several crops during the rainy and postrainy seasons *are* presented in Table 2.

The profile-moisture curves also can be used to follow throughout the season the amount and rate of extraction of water by roots and to relate observed changes in those rates to the amount of roots and the available-water content at different profie depths.

Changes in volumetric water content with depth and time in an Alfisol profile in rainfed and in irrigated millet crops are plotted in Figure

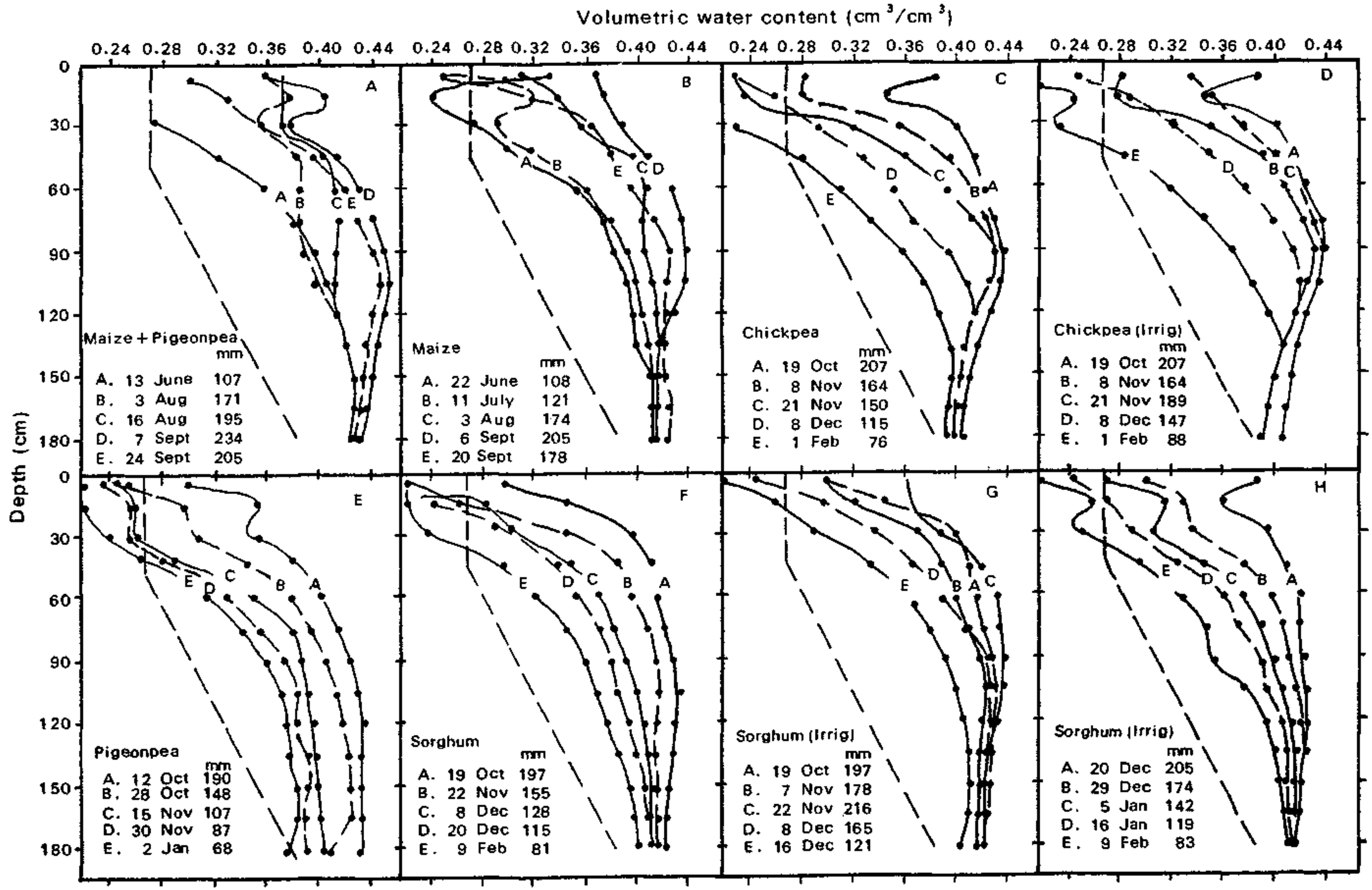

Figure 4. Moisture profiles of cropped deep Vertisols during the rainy and postrainy seasons.

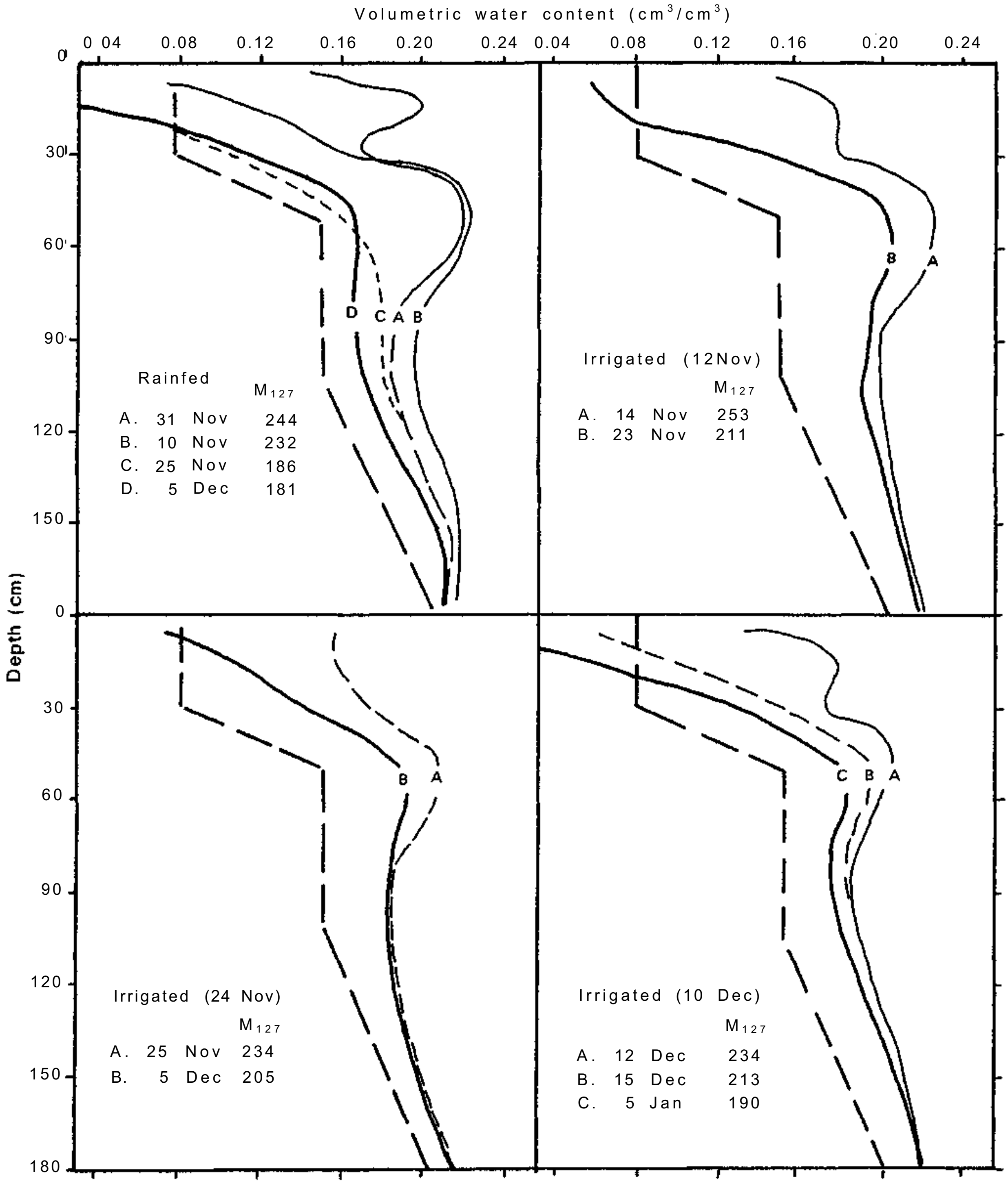

Figure 5. Moisture profiles of rainfed and irrigated pearl millet on an Alfisol.

6. The curves indicate that the rainfed crop removed water progressively with depth and time to a depth of 1 during the first 6 weeks of growth, at which time the plant-extractable moisture to a 60-cm depth was more than 80% depleted. Subsequent water use was confined to the 60- to 150-cm depth and essentially ceased 2 weeks later. The irrigated crop used the profile

Table 1. Postrainy-season water balances for rainfed sorghum on a deep Vertisol.

Period	Rainfall	Open pan evaporation	Profile water change	Evaporation	Transpiration T_m	Te	Tm/Ep
19 Oct-7 Nov	17	107	-26	21	22	11	0.20
7 Nov-22 Nov	5	75	-28	7	26	31	0.35
22 Nov-8 Dec	8	65	-27	1	34	45	0.52
8 Dec-29 Dec	20	98	-33	0	53	69	0.54
29 Dec-16 Jan	17	75	-23	6	34	48	0.45
16 Jan-9 Feb	5	127	- 3	5	3	46	0.02
Total	72	547	-144	40	176	250	0.32

Table 2. Seasonal water balances for several crops on a deep Vertisol.

Crop	da	P	I	E_P	E*	AM	L	E	R	D	T_m	Te
						Rainy season						
Maize/pigeonpea	92	408	-	496	217	86	322	84	4	14	220	287
Maize/pigeonpea	103	466	-	573	253	82	384	172	-	-	212	198
Maize	103	466	-	573	253	84	382	174	-	-	208	194
Maize	92	408	-	497	222	39	369	71	5	42	251	326
Maize	90	408	-	484	216	62	346	66	3	36	241	319
						Postrainy season						
Pigeonpea	121	122	-	570	108	-126	248	28	-	-	220	391
Pigeonpea	100	104	-	471	108	-135	239	43	-	-	196	298
Chickpea	105	47	-	503	64	-150	197	35	-	-	162	242
Chickpea	88	104	-	420	107	- 97	201	58	-	-	143	224
Sorghum	115	72	-	547	64	-144	216	40	-	-	176	250
Irrig. Chickpea	105	47	67	503	79	-135	249	36	-	-	213	281
Irrig. Sorghum	115	72	165	547	102	-132	369	51	-	-	318	284

da = Days
P = Rainfall (mm)
I = Irrigation (mm)
Ep = Open-pan evaporation (mm)
E* = Potential soil evaporation (mm)
AM = Change in profile moisture (mm)
L = Total water loss (mm)
E = Soil evaporation (mm)
R = Runoff (mm)
D = Drainage beyond 187 cm (mm)
Tm = Mass-balance transpiration (mm)
Te = Energy-balance transpiration (mm)

moisture to a depth of 90 cm following each of the profile-recharging irrigations. Late-season extraction from the irrigated plots also extended to 150 cm, so that the final profile-water contents of the irrigated and rainfed plots were similar. Profile-water extraction by the irrigated crop continued for 4 weeks beyond cessation in the nonirrigated plots.

The progressive depletion of the profile water is clearly shown by the changes in capillary potential with time at various depths in the nonirrigated plot (Fig. 6). These data also show that root extraction essentially ceased by 10 December, 8 weeks after sowing. At that time the potential at 30 and 45 cm had reached -15 bars. The continued fall in potential beyond -15 bars at 15 cm is attributed to moisture loss by evaporation. It is concluded that the roots at depths below 50 cm were not enough to withdraw water at the rate needed to maintain the millet crop. It therefore essentially stopped growing even though the capillary potential at 60- and 75-cm — and presumably also greater — depths was above the wilting point.

The rate of water extraction from various profile positions computed from the soil-

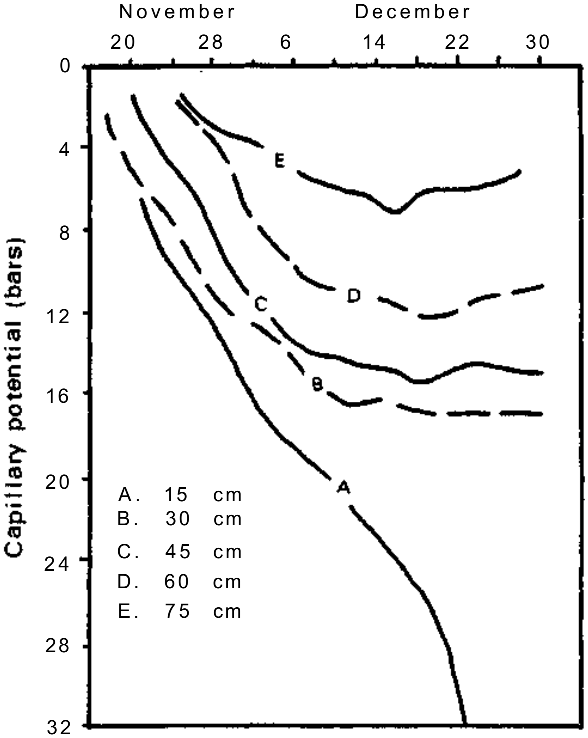

Figure 6. Capillary potentials during profile depletion under rainfed pearl millet on an Alfisol.

moisture profile curves for the irrigated millet crop is plotted in Figure 7. The general agreement in the distribution of roots and the rates of water extraction is reasonably good, and is consistent with the view that during these periods the crop was not seriously stressed and that the supply of water at various depths in the profile was not limiting water-uptake rates.

Detailed water balances computed for several periods for both the rainfed and irrigated crops are presented in Table 3. Evaporation constituted less than 20% of the water lost by the irrigated and the rainfed plots. For the rainfed crop the values for T_m and T_e were similar during the first 6 weeks, indicating that the crop was not experiencing moisture stress. However for the next 3 weeks $T_m << T_e$, indicating severe moisture stress. In the irrigated crop, T_m was quite similar to T_e throughout the entire 80-day growing season. Yields of the irrigated and rainfed crops were 1800 and 1100 kg/ha, respectively. These yields divided by the amount of water transpi red gave water-use efficiencies for the two crops of 150 and 140 kg grain per centimeter of water transpired.

Changes in available moisture at four depths in the irrigated plots are presented in Table 4.

Table 3. Water balances for pearl millet sown 13 October on reinfect and irrigated Alfisol.

	da	P	E_P	E*	β	AM	L	E	Tm	Te
					Rainfed pearl millet					
31 Oct-10 Nov	10	18	52	17	0.70	- 12	30	12	18	16
10 Nov-25 Nov	15	10	67	14	0.35	- 46	56	5	51	44
25 Nov-5 Dec	10	2	42	3	0.40	- 5	7	1	6	25
5 Dec-15 Dec	10	0	49	2	0.60	- 3	3	1	2	20
Total	45	30	210	36	-	- 66	96	19	77	105
					Irrigated pearl millet					
31 Oct-10 Nov	10	18	52	17	0.70	- 15	33	12	21	16
14 Nov-23 Nov	9	5	38	10	0.35	- 42	47	4	43	25
25 Nov-5 Dec	10	2	40	12	0.25	- 29	31	4	27	30
12 Dec-28 Dec	16	0	63	9	0.38	- 30	30	3	27	39
28 Dec- 5 Jan	8	0	37	2	0.60	- 14	14	1	13	15
Total	53	25	240	50	-	-130	155	24	131	125

da = Days
P = Rainfall (mm)
Ep = Open-pan evaporation (mm)
E* = Potential soil evaporation
β = Light transmission coefficient
AM = Change in profile moisture (mm)
L = Total water loss (mm)
E = Soil evaporation (mm)
Tm = Mass-balance transpiration (mm)
Te = Energy-balance transpiration (mm)

Irrigations on 12 and 24 November and on 10 December recharged the 0- to 22- and 22- to 52-cm layers, which were subsequently depleted by root extraction. These layers accounted for nearly 90% of the water used by the millet crop. The efficiency with which the crop used the storage capacity of the four profile layers is given by the capacity-use factor (CUF) which is defined as the seasonal withdrawal divided by the layer capacity for each layer. The CUF values of 2.9,1.2,0.55, and 0.15 for the 0- to 22-, 22- to 52-, 52- to 82-, and 82- to 127-cm layers emphasize the fact that the pearl millet root system was ineffective in its exploitation of available water below 52 cm in this Alfisol profile.

The changes in available water in six layers of the deep-Vertisol profile under rainfed and irrigated sorghum during the postrainy season are summarized in Table 5. For the rainfed crop, the small rains during the growing season only partially recharged the 0- to 22-cm layer. The

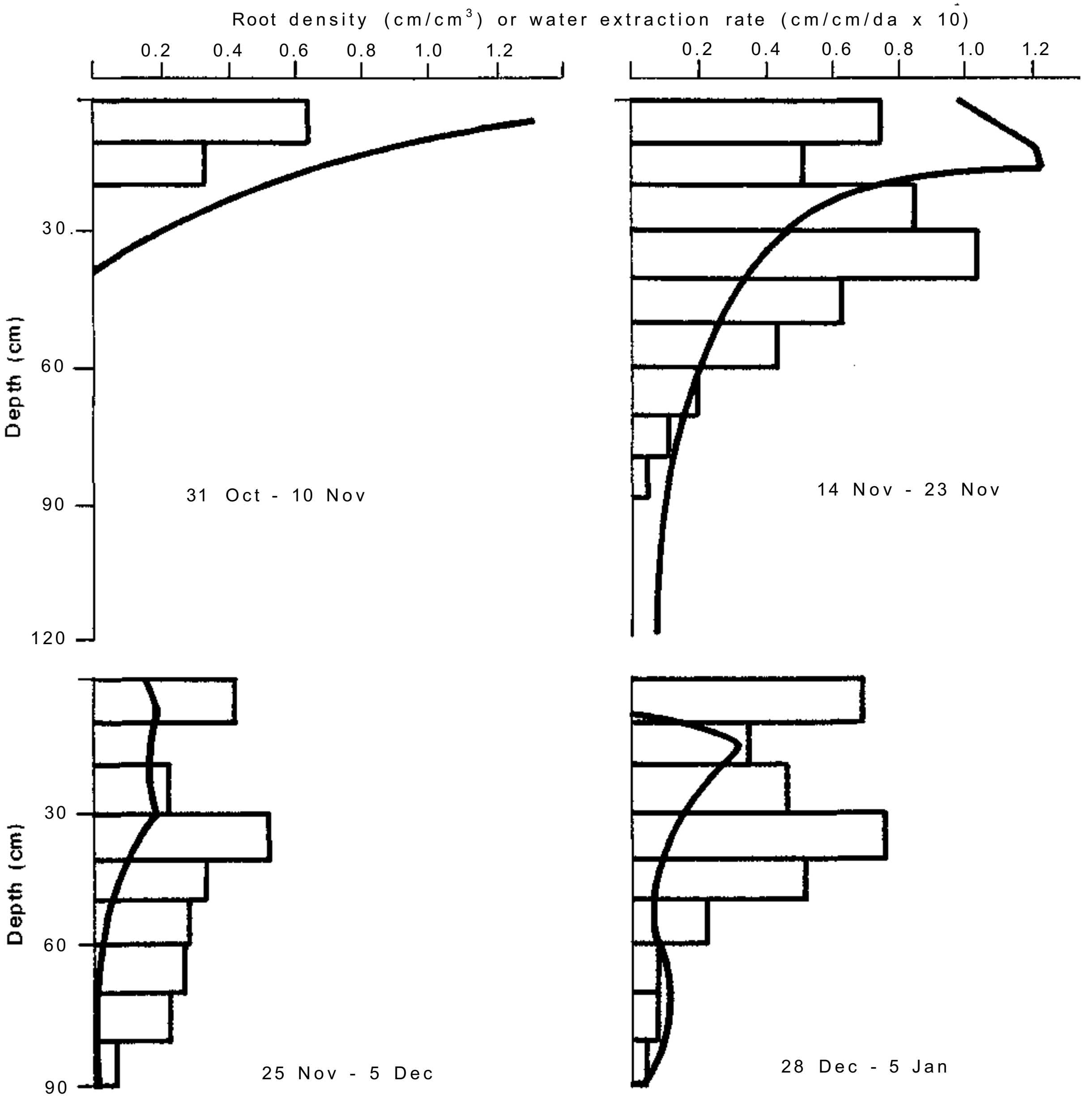

Figure 7. Root densities (bars) and water-extraction rates (lines) of pearl millet on an Alfisol.

Table 4. Seasonal changes in available water in four layers of an Alfisol under irrigated pearl millet.

	Depths (cm)					
	0-22 (mm)	22-52 (mm)	52-82 (mm)	82-127 (mm)	0-127 (mm)	CU[a] (mm)
Oct 31	22	28	18	16	84	0
Nov 10	4	25	20	21	70	14
12[b]	0	24	20	21	65	19
14	19	28	21	22	90	19
23	0	18	15	18	51	58
25	17	24	14	15	70	58
Dec 5	3	15	12	14	44	84
10[c]	0	10	11	13	34	94
12	17	23	12	17	69	94
15	2	19	12	17	50	113
28	1	15	10	13	41	122
Jan 5	0	12	8	14	34	129
Seasonal use	75	39	11	4		129
Layer capacity	26	33	20	27	106	
CUF[d]	2.9	1.2	0.55	0.15		

a. Cumulative use (mm)
b. Capacity use factor
c. Extrapolated from 31 Oct to 10 Nov losses
d. Extrapolated from 25 Nov to 5 Dec losses

deeper layers each lost water progressively by root extraction. In the irrigated plots the recharging action of rains was supplemented by irrigations on 18 November and 19 December, which recharged the entire profile. As a result of those cyclical rechargings and depletions, the total water extracted from the various soil layers exceeded the capacity of those layers. The capacity-use factors for the irrigated sorghum were 2.6, 1.8,1.2,1.1,0.9, and 1.0. For the rainfed crop the corresponding CUF values were 1.7, 0.8, 0.8, 0.6, 0.5, and 0.5.

Of the 175 mm of water transpired by the rainfed sorghum, the percentages obtained from each of the six depths of the profile were 28, 23, 20, 12, 9, and 8. The corresponding values for the irrigated crop, which transpired 310 mm during the 112-day growing season, were very similar — 25, 30, 18, 13, 9, and 8. These data suggest that there was little difference in root-development patterns of these rainfed and irrigated sorghum crops and that the amount of available water in the various layers was the dominant factor influencing the time-and depth-patterns of water use.

The amount of water extracted from deep Vertisol by roots of rainfed pigeonpea during five periods of the postrainy season are summarized in Table 6. The rain that occurred during the season only partially recharged the upper two layers of the profile. Data in Table 6 were calculated from the profile-depletion curves and from daily water balances for the periods following rains. Fortheseason, the crop obtained 57% of its water from the upper 52 cm of the profile. The CUF values for the six depths were 2.5, 0.9, 0.6, 0.6, 0.8, and 1.0. These indicate that the pigeonpea roots were effective in removing water throughout the entire 187-cm Vertisol profile.

The effects of the depletion of available moisture on water uptake by sorghum and chickpea from various depths in a Vertisol profile are shown in Figure 8. Both crops were sown in mid-October. The rainfed and irrigated plots were treated alike priortothe profile-recharging

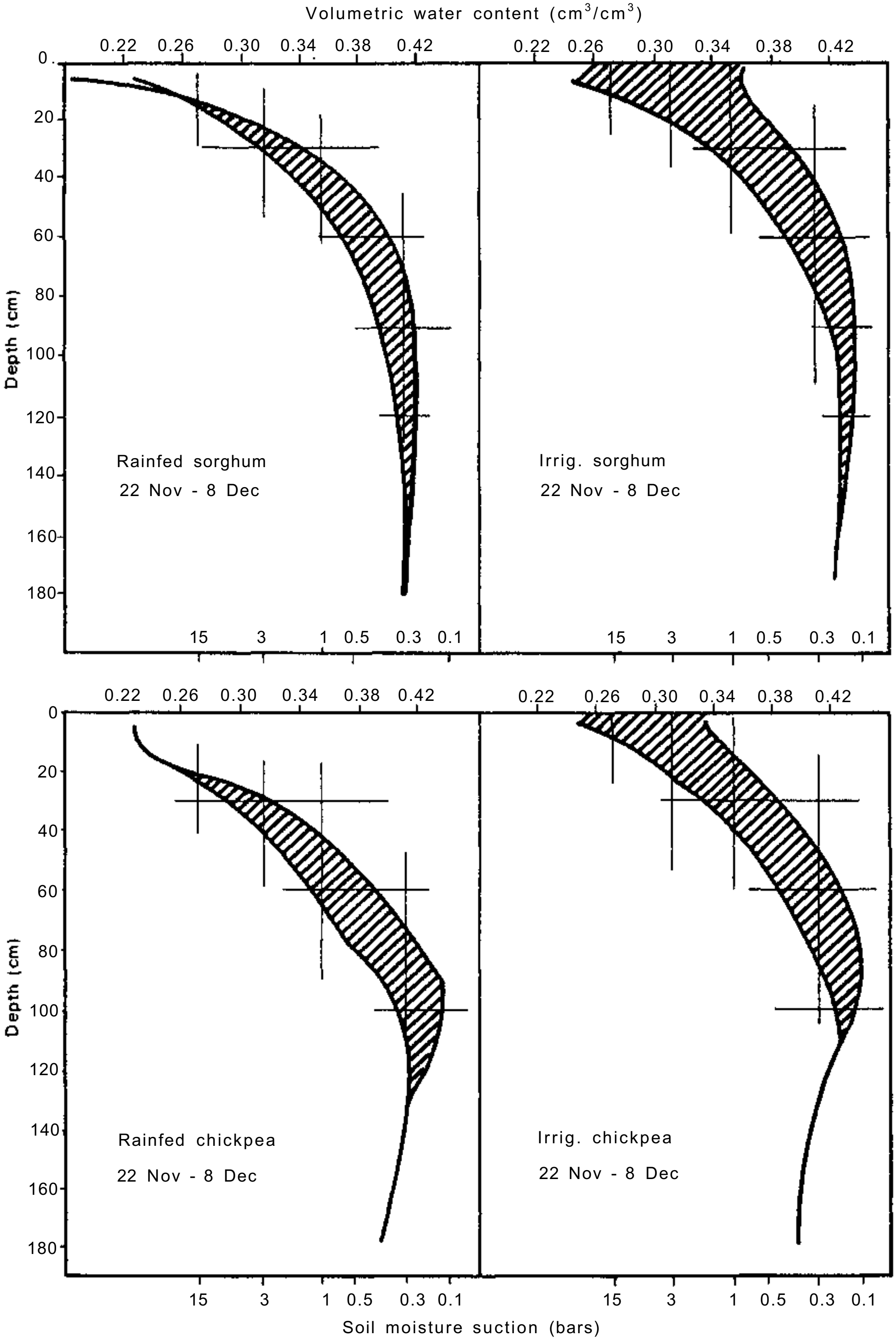

Figure 8. Water-extraction profiles of rainfed and irrigated sorghum and chickpeas on a deep Vertisol.

Table 5. Plant-available water (mm) at six depths in a deep Vertisol during the postrainy season.

	Rainfed sorghum[a]							Irrigated sorghum[b]						
Depths (cm)	0–22	22–52	52–82	82–112	112–142	142–187	TOTAL	0–22	22–52	52–82	82–112	112–142	142–187	TOTAL
Capacity (mm)	30	50	45	36	29	24	214	30	50	45	36	29	24	214
Oct 19	23	41	38	33	25	21	181	23	41	38	33	25	21	181
Nov 7	20	35	35	31	23	18	162	20	35	35	31	23	18	162
17[c]								10	30	34	29	22	17	142
18[d]								30	50	45	36	29	24	214
Nov 22	5	28	34	29	22	16	134	32	42	43	36	26	21	200
Dec 8	4	18	25	23	19	15	104	4	27	34	31	26	18	140
16	2	12	19	18	14	12	77	0	14	23	22	19	13	91
19[e]								0	8	19	19	16	11	72
20								34	41	39	31	25	19	189
29	4	5	18	18	15	14	74	24	27	34	29	24	18	156
Jan 5	−2	1	14	13	12	10	50	17	18	27	25	22	17	126
9								22	20	25	23	21	17	128
16	2	3	13	12	10	8	48	1	12	22	21	20	16	92
Feb 9	−5	0	13	16	11	9	49	0	3	14	14	15	13	59
Seasonal use	50	41	35	21	15	13	175	77	91	55	38	26	23	310

a. Total rain during season, 72 mm.
b. Irrigations on 18 Nov and 19 Dec.
c. Computed as 10/15 of 7–22 Nov loss from rainfed plots.
d. Assumed full capacity after 18 Nov irrigation.
e. Computed as 11/8 of 8–16 Dec change.

Table 6. Profile water use (mm) by pigeonpea from a deep Vertisol during postrainy season.

Calendar dates	Days	Depth (cm) 0-22	22-52	52-82	82-112	112-142	142-187	Total
24 Sep-12 Oct	18	27	13	4	4	2	0	50
12 Oct-28 Oct	16	18	11	7	4	3	4	47
28 Oct-15 Nov	18	23	11	7	7	8	9	65
15 Nov-30 Nov	15	6	3	5	3	3	6	26
30 Nov- 2 Jan	33	5	5	4	2	2	4	22
Seasonal total	100	79	43	27	22	18	23	212

irrigation applied on 19 November. Th curves clearly show that total amount of water used and the position in the profilefrom which it was extracted during the 16-day period were each quite different for the rainfed and irrigated crops. Since it is reasonable to assume that in these plots the root system of the rainfed and irrigated crops was the same, the differences in water-uptake rates can be attributed to the greater depletion and higher soil-moisture suction that existed in the upper parts of the profile in the nonirrigated plots.

Thedata discussed herein illustrate the role of the soil profile in modulating the water supply and demand relationships that characterize crop production under SAT conditions. Quantitative field studies of the time and depth patterns of recharge and depletion of the soil profile provide a useful means of integrating, in agronomically relevant terms, the dynamic interaction of climatic, edaphic, and plant factors that determine crop producton.

The amount and timing of the rains as well as the size and rate of development of the crop canopy and of the root system strongly influence the performance of the soil profile as a means for providing the water supply for crop use. Thus during seeding and stand establishment, it is the plant-available water in the upper few centimeters of the profile that is important; consequently the effective storage capacity is small and the time required to deplete it is short. On the other hand, when the crop is fully established, its root system may have access to a profile-storage capacity that may be 50 times the daily transpiration requirement; hence the system will not experience rapid short-term change. An adequate agronomic description of the soil profile as a moisture reservoir for the crop should indicate where and when, as well as how much, water is available throughout the entire growing season.

The Versatile Soil-Moisture Budget: Concepts and Application

Wolfgang Baier and Jim Dyer*

Summary

The Versatile Soil Moisture Budget (VB) considers the major soil and plant processes that involve water. At the same time, the model is simple to understand and use. It represents a compromise between a completely statistical approach, where no parameterizing of physical processes is attempted, and a mathematical approach, in which only physical parameters are used. Although the purely physical or mathematical approach is often preferable, it is not usually possible since root distribution and hydraulic conductivity values are difficult to measure and are seldom available. The VB is the result of a semiempirical approach for which the necessary coefficients have been statistically derived for the most common field and crop situations. The performance of the budget has also been well verified in many applications.

Each method for measuring soil moisture has certain inherent shortcomings, but all have the additional limitation that the results of site measurements must somehow be integrated over space in order to be useful for agricultural applications. Because of these instrumental limitations, there have been many attempts to compute evapotranspiration and thereby, indirectly, soil-moisture content, by means of physical methods or empirical formulae. The physical methods for modeling soil-moisture transfer and distribution overthe soil profile are at a stage where they would be useful in research but not for agricultural applications where information over time and space is required. On the other hand, climatological water-budgeting techniques have been widely used in research and applications. Such techniques are designed to determine irrigation-water requirements in soils under nonwater-stress conditions or the distribution of soil water in soils under limiting soil-moisture conditions. Literature reviews of the various approaches are available in research papers and in several WMO (World Meteorological Organisation) publications (see References). A typical example is the Versatile Soil-Moisture Budget, described here in detail.

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Design of the Versatile Budget

The Versatile Budget (VB) is essentially a meteorological water budgeting procedure. Because of its design, it is more versatile than earlier attempts to calculate soil moisture from climatic data (Baier and Robertson 1966). The VB was specifically developed to accept daily data of precipitation and estimates of potential evapotranspirations (PE) for simulating variations in daily soil-moisture content by making use of generally accepted concepts of water movement into the soil and water loss from the soil through actual evaporation from an uncropped soil surface or through evapotranspiration from crops (AE).

A flowchart (Fig. 1) plots the water pathways in the soil and roots, to and from the atmosphere, as simulated in the VB. The various computational steps in the model, including the distinction between soil-moisture extraction and soil-moisture recharge are also shown.

Soil Moisture Extraction

Water is withdrawn simultaneously from different depths of the soil profile in relation to the

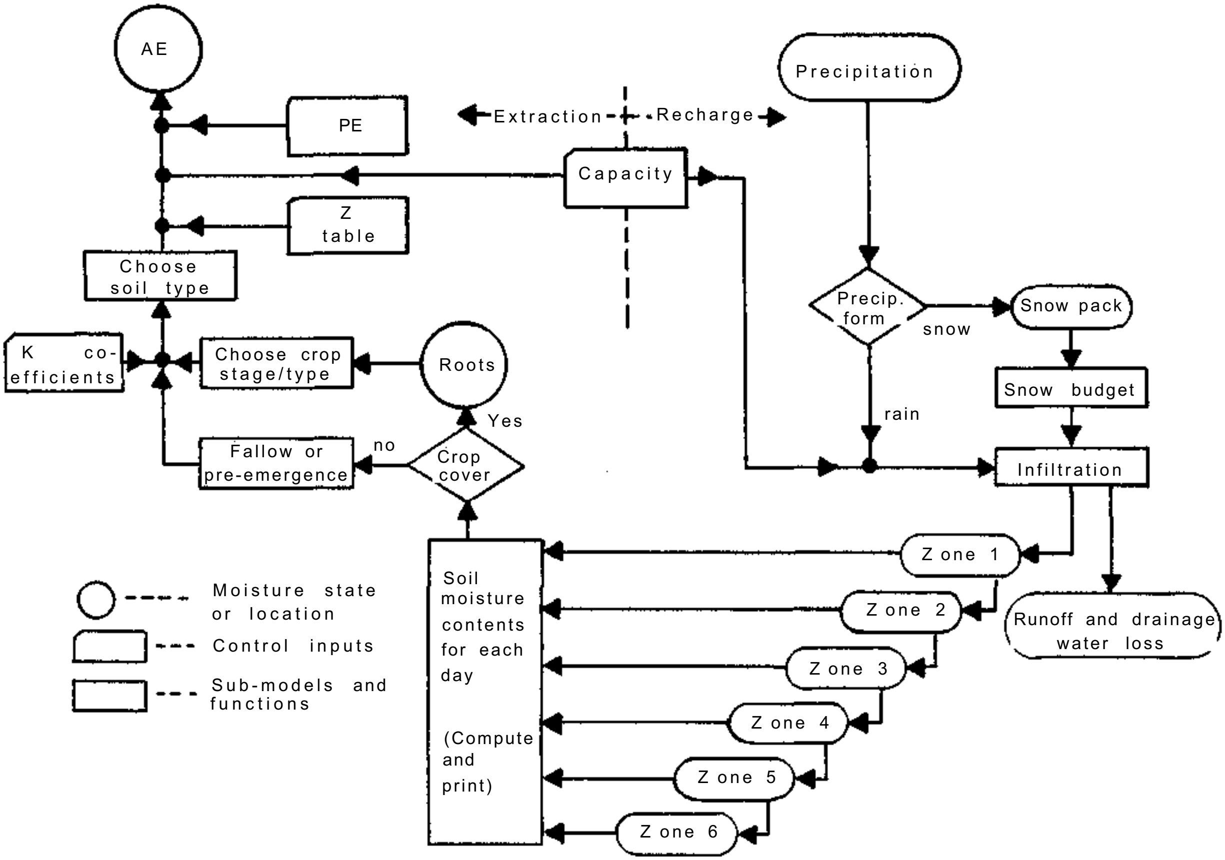


Figure 7. Soil root-atmosphere pathways for water in the versatile soil-moisture budget.

rate of PE, rooting patterns of crops, different soil-moisture release characteristics, and the available water in each of six zones of specified water-holding capacities. PE is used as a climatic parameter of the potential rate of evapotranspiration from a dense crop freely supplied with water (WMO 1966b). The general equation of the VB for estimating daily AE from PE is as follows:

$$AE_i = \sum_{j=1}^{n} \left[k_j \frac{S'_j(i-1)}{S_j} Z_j PE_i \right] \qquad (1)$$

Where

= actual evapotranspiration for day i ending at the morning observation of day i +1

$\sum_{j=1}^{n}$ = summation carried out from zone j = 1 to zone j = n

k_j = coefficient accounting for soil and plant characteristics in the jth zone

$S'_j(i-1)$ = available soil moisture in the jth zone at the end of day i -1 (that is, at the morning observation of day i)

S_j = capacity for available water in the jth zone

Z_j = adjustment factor for different types of soil dryness curves

PE_i = potential evapotranspiration for day i

Although this equation gives the total AE, accumulated over all zones (1 to n), the effect on AE of the available water content of each zone (j) must be computed separately.

Standard Zones

The total volume of plant-available soil moisture in the soil profile is subdivided into six zones of varying capacities. The amount of moisture held in each zone is arbitrary, but a standard relationship for the zonal capacities has been adopted (Table 1). The six standard zones contain respectively 5.0, 7.5, 12.5, 25.0, 25.0, and 25.0% of the total plant-available moisture-holding capacity of the soil profile. Thus, a zone is defined as a fraction of the total available soil moisture. Because the root distribution differs in depth from soil to soil, the location of the zones also differs, but not the fractional subdivision of the total available soil moisture. The adoption of standard zones makes it possible to use one set of crop coefficients for a particular crop in any type of soil, because it is assumed that the uptake of available water by crops always follows a characteristic pattern that depends on plant-rooting habits. For water-budgeting procedures, it is irrelevant at which depth the water is located within the soil profile.

Crop Coefficients

Crop coefficients (k) express the amount of water extracted by plant roots from the different zones during the growing season as a function of PE. To simulate this water uptake, the k-coefficients change during the growing season on a calendar basis, but preferably according to crop-development stages or on a biometeorological time-scale basis, such as proposed by Robertson (1968). The transition dates between crop stages must be read into the program for each year. The k-coefficients presently in use have been determined by iterative comparisons between computed and measured soil moisture or were estimated to resemble the most probable crop-rooting pattern under the prevailing environmental conditions. Table 2 lists the k-coefficients developed so far. The distribution of k values over depth corresponds with the standard zones mentioned above; however, it is possibleto redefine these k-coefficients to correspond to a new set of zonal capacities.

Crop Coefficient Adjustment

In comparisons between observed and estimated soil moisture under nonirrigated crops, Baier (1969a) found that during drought periods plant roots absorbed, from the relatively moist lower layers, comparatively more water than they did from a uniformly moist soil profile. This is simulated in the VB by decreasing the k-coefficients for the upper zones, where water is no longer or is less readily available, and by giving more influencetothe lowerzones, where water is still available. The use of this adjustment and the date of its commencement are optional. The adjustment takes the form:

$$k'_j = k_j + k_j \sum_{m=1}^{m=j-1} k_m \left[1 - \frac{S'_m(i-1)}{S_m}\right] \qquad (2)$$

where

k'_j = adjusted k-coefficient for the jth zone
$S'_m(i-1)$ = available soil water in the mth zone
S_m = capacity for available water in the mth zone.

Soil Moisture Availability to Plants

For the purpose of this budget, plant-available soil moisture is considered to be the amount of

Table 1. Standard soil-moisture zones and available water In each zone for use In the Versatile Budget (VB).

Zone	Percent of total capacity	Total plant-available water (inches) 2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
		Available water (inches)							
1	5.0	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
2	7.5	0.15	0.23	0.30	0.38	0.45	0.53	0.60	0.68
3	12.5	0.25	0.38	0.50	0.63	0.75	0.88	1.00	1.13
4	25.0	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25
5	25.0	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25
6	25.0	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25

Table 2. k-coefficients presently available for several crops and cropping practices.

Zone	1	2	3	4	5	6	
Stages			Brome grass				
Dormant season	0.50	0.20	0.10	0.04	0.02	0.01	
Growing season	0.55	0.19	0.17	0.08	0.03	0.01	
			Alfalfa				
SS-FC	0.50	0.20	0.15	0.12	0.08	0.05	
FC-1st	0.50	0.25	0.23	0.22	0.15	0.10	
1st-FC	0.50	0.22	0.18	0.15	0.15	0.10	
FC-2nd	0.50	0.25	0.25	0.20	0.18	0.12	
2nd-FC	0.45	0.25	0.20	0.20	0.20	0.15	
			Small grain[a]/corn				
P-E or							Stages
R-P[b]	0.40	0.15	0.12	0.10	0.02	0.01	P-E
E-J	0.40	0.20	0.13	0.12	0.03	0.02	E-T
J-H	0.40	0.25	0.15	0.12	0.10	0.03	T-Si
H-S	0.40	0.30	0.20	0.15	0.10	0.05	Si-Ee
S-R	0.40	0.30	0.20	0.15	0.07	0.03	Ee-H

Symbols used to define stages

Small grain	Corn	Alfalfa
P planting	T tasseling	SS start-growing season
E emergence	Si silking	FC full cover
J jointing	Ee ear emergence	1st first cut
H heading		2nd second cut
S soft dough		
R ripening		

a. Wheat, barley, millet.
b. Fallow or bare soil.

moisture over the rangefrom field capacity (1/3 atm or pF = 2.7)to permanent wilting (15atmor pF = 4.2). Contradictory viewpoints exist on the availability of soil moisture over this range for growth and transpiration. A review of literature pertaining to soil-moisture regime experiments (Baier 1968) suggested that the relationship between available moisture in the soil and AE : PE ratio still depends on physical characteristics of the soil, even though all other factors — such as plant physiological characteristics of water uptake and atmospheric demand as reflected in the PE rate — are taken into account.

Typical relationships between available soil moisture and AE : PE ratio are plotted in Figure 2. Baier (1969b) discussed these relationships in detail and demonstrated that the soil-moisture estimates from the VB differed significantly when extreme types (e.g., C and F) were used, whereas those for two similar types (e.g., C and D, or B and F) were very close, and the error was probably within the precision of most methods for soil-moisture determination. The decision as to which type to use can be based on comparisons between observed and estimated soil moisture by testing different relationships in each computer run or on existing knowledge of moisture-retention characteristics of soils (Salter and Williams 1965).

The VB makes provision for using the various relationships shown in Figure 2 through the so-called Z-tables (Table 3). These tables can be better understood by considering the general case of Equation (1), where only one zone is considered and the k-coefficient is set to 1. Z can

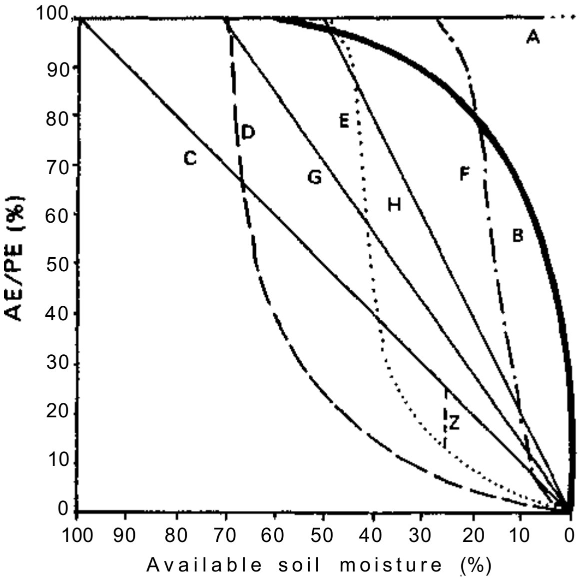


Figure 2. Various proposals for the relationships between AE:PE ratio and available soil moisture (after Baier and Robertson 1966).

then be expressed as a function of the AE : PE ratio as follows:

$$Z = \frac{AE}{PE} \Big/ \frac{S_j(i-1)}{S_j} \qquad (3)$$

The correct value of Z is selected from the 100 possible values in the appropriate Z-table by using the percent available water to define a subscript or index (I_z).

Z = Z-table (I_z)
where $I_z = (S'_j/S_j)\ 100$

Values for Z_j are then substituted into Equation (1), based on the percent available water in each zone (j).

The program can facilitate two Z-tables at once. This feature can be used in two ways:

a. In heterogeneous soils having two distinct textural horizons, one Z-table can be applied to the upper zones and the second to the lower zones. If a homogeneous soil is assumed, one Z-table is used throughout all six zones.
b. Continued experimentation has shown that the relationships in Figure 2 depend not only on the soil type, but also on whether an active root system is present or if the soil is fallow. Therefore in simulating the soil-moisture distribution in a crop-fallow rotation, one table (e.g. Z-TableG) can be used in cropped years and another table (e.g. Z-Table D) can be used in fallow years.

Brief descriptions of the Z-tables available (A to H) and some guidelines for their selection and use are available elsewhere (Baier et al. 1972).

Soil-Moisture Recharge

In the VB, recharge of soil water is entirely the result of precipitation, either as rain or snowfall. Since there is no allowance made for moisture conduction between zones, precipitation must be partitioned out to the six zones, just as AE was partitioned out to account for water loss from each zone. The factors considered in recharging soil moisture are rainfall, snowmelt, surface runoff, infiltration, subsurface drainage, and the percent soil moisture on day i-1.

Runoff and Infiltration

To account for water recharge through rainfall, a simplified relationship between soil moisture in the top zone, daily precipitation total, and runoff is included in the VB. On days with P<1 1.00 inch, the total amount of precipitation is considered to infiltrate into the soil. On days with P>1.00 inch, infiltration (Infl) into the soil is less than the daily rainfall, since it is limited by the moisture present in the top zone of soil, and is computed as follows:

$$Infl_i = 0.9177 + 1.811 \log RR_i - 0.97\, [S_j'(i-D/S_j] \log RR_i \qquad (4)$$

where

RRi	=	rainfall on day i
S'_j (i-1)	=	soil moisture in the jth zone on day i-1
S_j	=	availablewatercapacity of the jth zone
	=	1

The remainder of the daily rainfall is assumed to be lost as runoff. Equation (4) was taken from Linsley, et al. (1949).

Table 3. Z-tables used in the VB accounting for different moisture-release characteristics.

A TABLE

99.99	50.00	33.00	25.00	20.00	16.66	14.28	12.50	11.11	10.00
9.09	8.33	7.69	7.14	6.67	6.25	5.88	5.56	5.26	5.00
4.76	4.55	4.35	4.17	4.00	3.85	3.70	3.57	3.45	3.33
3.23	3.13	3.30	2.94	2.86	2.78	2.70	2.63	2.56	2.50
2.44	2.38	2.33	2.27	2.22	2.17	2.13	2.08	2.04	2.00
1.96	1.92	1.89	1.85	1.82	1.79	1.75	1.72	1.69	1.67
1.64	1.61	1.59	1.56	1.54	1.52	1.49	1.47	1.45	1.43
1.41	1.39	1.37	1.35	1.33	1.32	1.30	1.28	1.27	1.25
1.23	1.22	1.20	1.19	1.18	1.16	1.15	1.14	1.12	1.11
1.10	1.09	1.08	1.06	1.05	1.04	1.03	1.02	1.01	1.00

B TABLE

10.00	10.00	8.33	7.50	7.40	7.16	7.00	6.87	6.44	6.00
5.81	5.58	5.38	5.21	5.00	4.75	4.52	4.33	4.16	4.00
3.86	3.73	3.60	3.50	3.40	3.31	3.22	3.14	3.07	2.97
2.90	2.81	2.76	2.68	2.63	2.55	2.49	2.44	2.38	2.33
2.26	2.24	2.18	2.13	2.11	2.06	2.02	1.97	1.94	1.92
1.88	1.85	1.81	1.78	1.76	1.73	1.70	1.67	1.66	1.63
1.60	1.58	1.56	1.53	1.52	1.50	1.47	1.46	1.43	1.41
1.40	1.38	1.36	1.35	1.33	1.31	1.29	1.28	1.26	1.25
1.23	1.21	1.20	1.19	1.17	1.16	1.14	1.13	1.12	1.11
1.09	1.08	1.07	1.06	1.05	1.04	1.03	1.02	1.01	1.00

C TABLE

1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

D TABLE

0.00	0.00	0.00	0.00	0.20	0.16	0.14	0.13	0.11	0.10
0.09	0.16	0.15	0.14	0.13	0.13	0.12	0.17	0.16	0.15
0.14	0.18	0.17	0.21	0.20	0.19	0.22	0.21	0.24	0.23
0.26	0.25	0.27	0.29	0.29	0.30	0.32	0.34	0.36	0.35
0.36	0.37	0.37	0.39	0.40	0.41	0.43	0.46	0.47	0.48
0.49	0.50	0.54	0.56	0.56	0.59	0.61	0.64	0.66	0.68
0.70	0.76	0.79	0.83	0.85	0.91	1.00	1.03	1.16	1.41
1.40	1.38	1.35	1.34	1.33	1.31	1.29	1.28	1.26	1.25
1.23	1.21	1.19	1.18	1.17	1.15	1.14	1.13	1.12	1.11
1.10	1.08	1.07	1.06	1.05	1.04	1.03	1.02	1.01	1.00

E TABLE

0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
0.21	0.23	0.25	0.27	0.29	0.31	0.32	0.34	0.36	0.38
0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.60
0.65	0.65	0.70	0.71	0.74	0.78	0.81	0.91	1.05	1.25

Continued

Table 3. Continued

1.34	1.43	1.63	1.82	2.00	2.00	2.00	2.00	2.00	2.00
1.96	1.92	1.89	1.85	1.82	1.79	1.75	1.72	1.69	1.67
1.64	1.61	1.59	1.56	1.54	1.52	1.49	1.47	1.45	1.43
1.41	1.39	1.37	1.35	1.33	1.32	1.30	1.28	1.27	1.25
1.23	1.22	1.20	1.19	1.18	1.16	1.15	1.14	1.12	1.11
1.10	1.09	1.08	1.06	1.05	1.04	1.03	1.02	1.01	1.00
				F TABLE					
1.00	0.75	0.66	0.50	0.60	0.66	0.85	1.12	1.44	1.66
1.82	2.33	2.69	3.00	3.33	3.43	3.70	3.89	4.00	4.00
4.00	4.00	4.00	3.91	3.80	3.69	3.59	3.50	3.41	3.33
3.20	3.10	3.00	3.92	2.85	2.77	2.69	2.60	2.55	2.50
2.45	2.37	2.30	2.26	2.22	2.16	2.10	2.07	2.04	2.00
1.95	1.90	1.86	1.83	1.80	1.77	1.75	1.72	1.69	1.66
1.63	1.60	1.58	1.56	1.53	1.51	1.49	1.47	1.45	1.42
1.40	1.38	1.36	1.34	1.32	1.30	1.28	1.27	1.26	1.25
1.23	1.21	1.19	1.18	1.17	1.15	1.14	1.13	1.12	1.11
1.10	1.09	1.08	1.06	1.05	1.04	1.03	1.02	1.01	1.00
				G TABLE					
1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
1.40	1.38	1.35	1.34	1.33	1.31	1.29	1.28	1.26	1.25
1.23	1.21	1.19	1.18	1.17	1.15	1.14	1.13	1.12	1.11
1.10	1.08	1.07	1.06	1.05	1.04	1.03	1.02	1.01	1.00
				H TABLE					
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
1.96	1.92	1.88	1.85	1.81	1.78	1.75	1.72	1.69	1.67
1.64	1.61	1.59	1.56	1.53	1.52	1.49	1.47	1.45	1.43
1.40	1.38	1.35	1.34	1.33	1.31	1.29	1.28	1.26	1.25
1.23	1.21	1.19	1.18	1.17	1.15	1.14	1.13	1.12	1.11
1.10	1.08	1.07	1.06	1.05	1.04	1.03	1.02	1.01	1.00

The partitioning of infiltrated water to each zone is simulated by the function:

$$Infl_{ij} = [1 - ((S'_j(i-1)/S_j)b]\,infl_j \quad (5)$$

Inflij= new infiltration into each zone of soil
b = infiltration coefficient ranging from 0 to 1 and modifying the fraction of water infiltrating to the next zone. For b = 0: water content of each zone must reach field capacity before the remaining water infiltrates into the next zone. For b = 1: a fraction of the infiltration water percolatestothe next zone before field capacity is reached, depending on the moisture content of the upper zone(s).

This infiltration equation is applied only when the ratio of soil moisture to capacity in any zone is less than 0.9. The amount of water that can infiltrate into and remain in each zone cannot exceed the deficit (DEF) forthat zone (j) and day (i). The deficit is given by:

DEFji = Sj - S'j (i - 1) - AEji. (6)

Also, the amount of water that can be budgeted to the jth zone can never exceed the amount remaining from the total water infiltrated after water has been budgeted to zones 1 to j - 1. If, after all zones have been recharged, there is still infiltration water remaining, then this water is assumed to be lost to plant roots because of subsurface drainage. This means that the infiltration is distributed over the zones as a function of:

a. amount of infiltration
b. relative moisture content in each zone as determined by

c. b, an empirical coefficient which has been evaluated for a number of prairie soils.

It will be noted that for b = 1.0 and a moisture content of 50% of .capacity, only half of the infiltration amount is retained in this zone, whereas the other half is distributed over the lower zones as a function of their moisture contents. This feature of the infiltration equation is particularly useful in heavy-textured soils. Comparisons with observed soil-moisture data have shown that b = 1 in Solonetz soil at Vegreville and in Haverhill clay loam at Swift Current, whereas b = 0 in Mathilde loam at Ottawa.

Snow budget

In some applications in temperate climates it is necessary to calculate a daily soil-moisture content throughout the year, particularly when a reasonable soil-moisture estimate is required in spring as a starting point for water budgeting during the growing season. In climates where snow occurs, the snow is an important storage term in the hydrologic cycle. Thus, a simple snow budget for computing the amount of water penetrating the soil from snow is available. If the snow budget is not required, each snow coefficient is set to 1.0 and each temperature threshold is set to 0.0.

Verification of the VB model

Since development of the VB and its first publication (Baier and Robertson 1966), the model has been tested extensively against soil-moisture observations at Swift Current, Saskatchewan, Canada (Fig. 3) and has also been verified in a number of applications by other researchers. A brief review of these studies is available elsewhere (Baier et al. 1978).

In one test, data from a 2-year wheat/fallow crop rotation on a clay loam soil atSwift Current were used from 1970 to 1974 (Fig. 3). Three-times replicated measurements from five depths weretaken between seven and ten times from planting to harvest each year. These results show very good agreement for both crop and fallow fields in 1971 and 1972, while all other years are encouragingly close. These results were summarized in more detail by Baier et al. (1976).

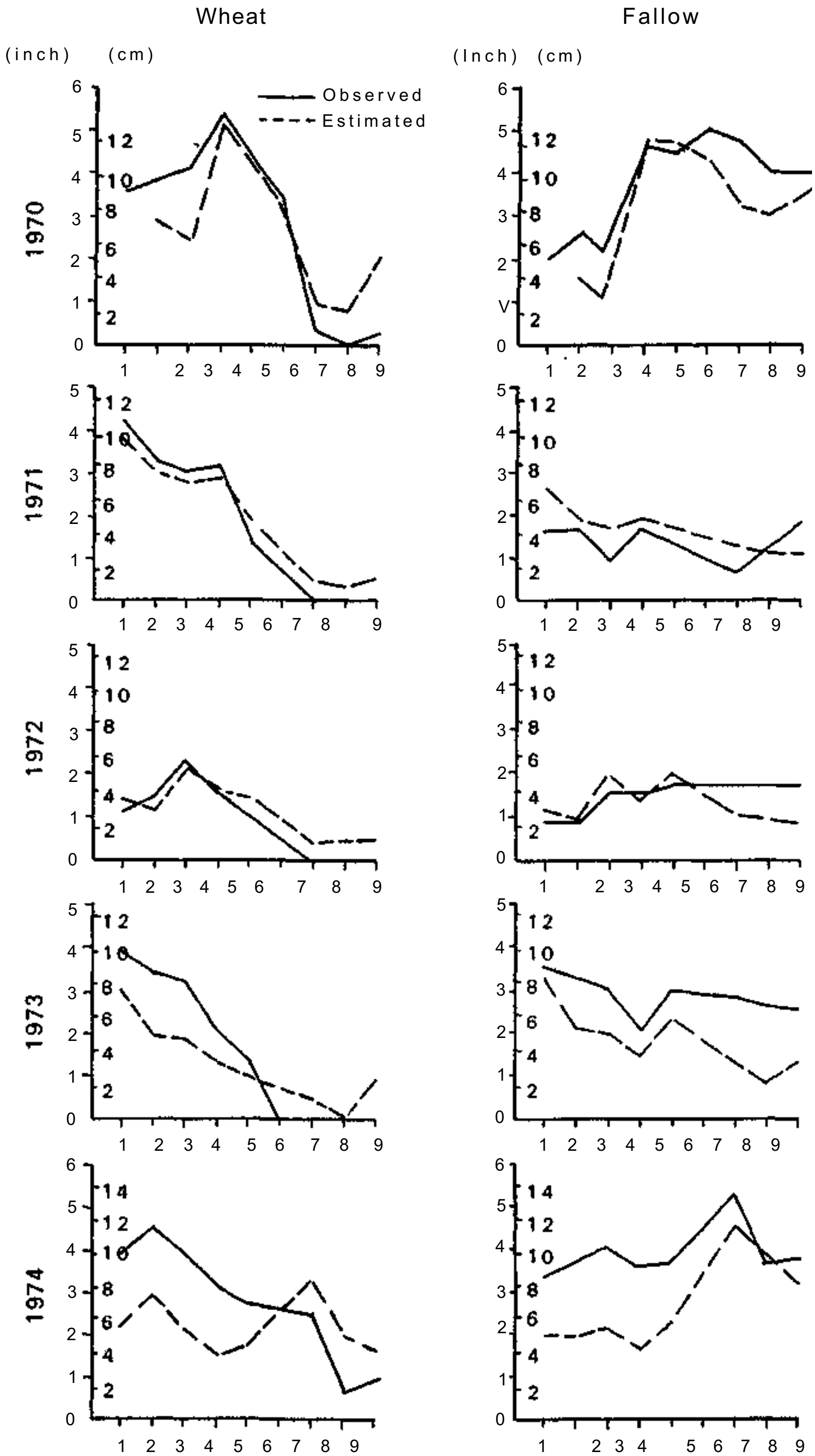
One verification which well illustrates the performance of the VB is shown is Figure 4, in which the model was applied to winter-wheat fields at Manhattan, Kansas for 1972-73.' The soil-moisture estimates were in good agreement with observations, and yield estimates based on VB values were reported to have agreed well with observed yields.

The final verification described here was provided by Baier (1972) using another independent set of observed soil-moisture data from 1937 to 1957. The results (Fig. 5) show observed and estimated soil-moisture reserves in spring at planting time under stubble and fallow lands, in a 2-year rotation system. In this case, the author was conducting an economic analysis of the advantages in water conservation of a 2-year crop-fallow rotation, as compared to continuous cropping.

Applications of the VB

The VB has found a wide range of applications from operational real-time monitoring of mois-

1. A. M. Feyerherm, 3 June 1975, Kansas State Univ., Statistical Laboratory, Calvin Hall 19, Manhattan, KA 66506, USA.



Stage code: 1 Seeding 4 5-leaf 7 Soft dough
2 Emergence 5 Shot blade 8 Harvest
3 3-teaf 6 Heading 9 Late fall

Figure 3. Observed and estimated soil-moisture contents vs the development stage of wheat on clay loam soils at Swift Current, Saskatchewan.

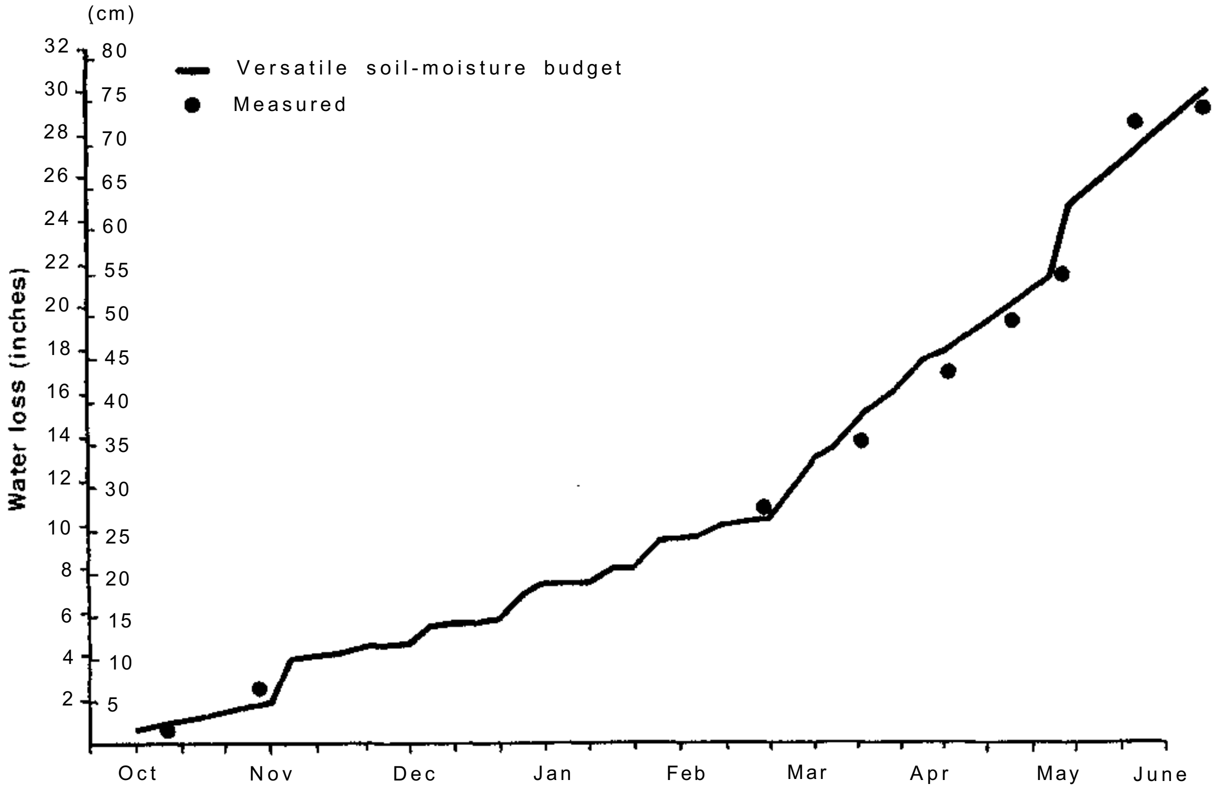


Figure 4. Estimated and observed soil-moisture contents at Manhattan, in a field of winter wheat, Kansas, 1972-1973

ture reserves on the western Canadian prairies to probability-analysis studies for planning farming operations. The VB has formed the basis of many crop-yield studies, several of which have already been discussed in terms of verification. Whether a highly detailed physically-based simulation or a regression-analysis approach is used, crop growth and yields can be more easily correlated with derived variables of actual evapotranspiration (AE) and soil moisture (SM) than with the primary components of climate, such as temperature, precipitation, and radiation (Q). Figure 6 illustrates such a scheme of derived agrometeorological data, used by Baier (1973) to define a three-variable regression model for wheat yield.

The VB is the basis of a soil-moisture evaluation project (SMEP) for Canadian prairies, in which the available soil water is monitored on a real-time basis throughout the growing season. Weekly maps of soil-moisture reserves have been generated for four available water capacities and under both fallow and wheat crop conditions. The project is in its third year and has so far been well received by many agencies, including the Canadian Wheat Board.

Application of the VB to tractability studies promises to be a valuable contribution to farm planners, particularly in the area of farm-machinery selection. The main criteria for selecting tillage and seeding equipment is the timely completion of planting in spring. An understanding of the restrictions on spring work time due to climate can be of major importance to agriculture extension agents working directly with farmers and to researchers doing detailed economic-simulation studies. Two studies of spring field-workday probabilities involving the VB have recently been completed by Agriculture Canada — one for the Atlantic provinces (Baier et al. 1978) and one for selected sites across Canada (Dyer et al., 1978).

Not all of the present applications have been discussed here, just as not all the possible

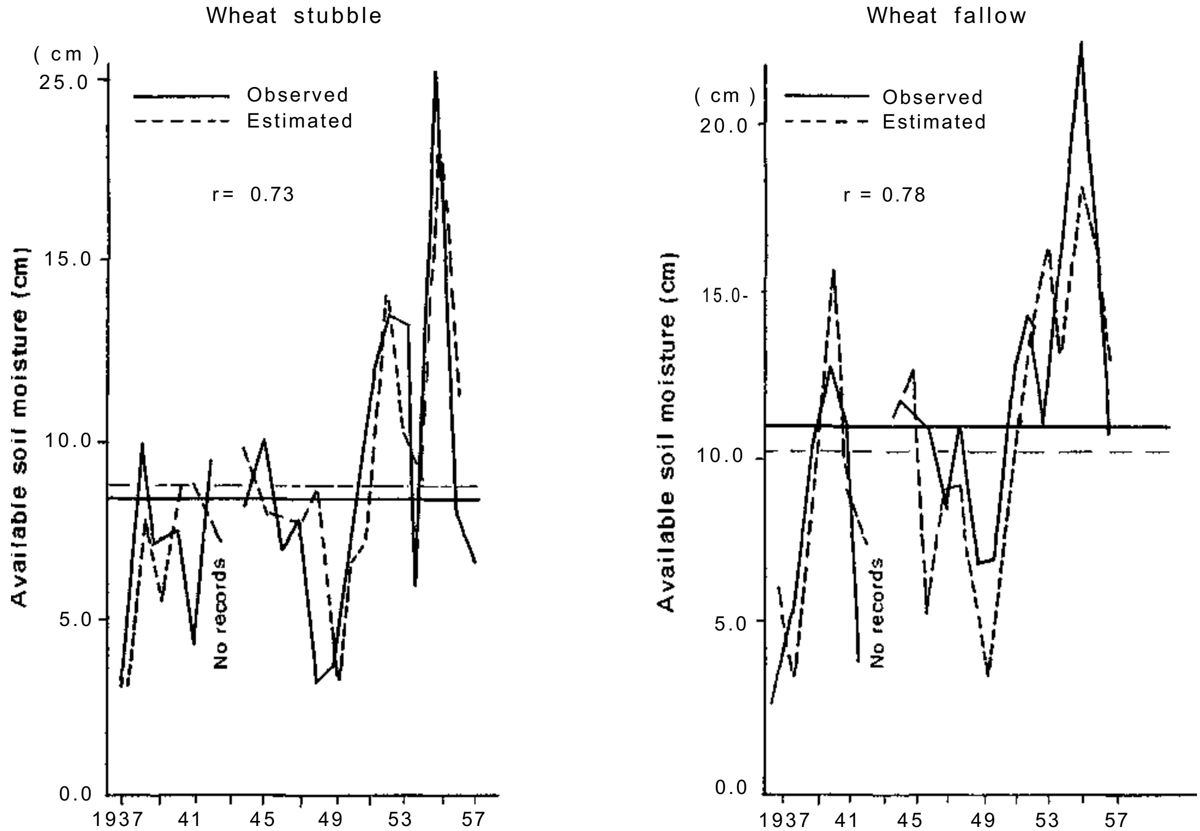


Figure 5. Observed and estimated available spring soil moisture in wheat stubble and wheat fallow lands at Swift Current, Saskatchewan, Canada. Parallel horizontal lines are mean values.

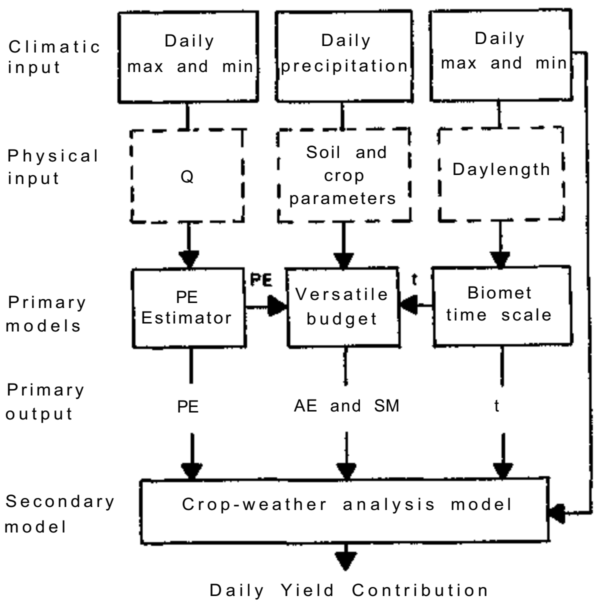


Figure 6. Input and output data of crop-weather analysis model.

future uses can be anticipated at this time. However, the examples chosen do illustrate the versatility of the budget.

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The Water Balance and Frequency Period of Vegetation

P. Franquin*

Summary

The ORBVCR water-balance model of ORSTOM adapted to the arid regions is presented. The model uses rainfall, potential evapotranspiration, and soil-moisture storage capacity as the inputs. It utilizes Eagleman's relationships to calculate actual evapotranspiration. The precipitation exceeding maximum soil moisture storage capacity is considered as runoff or drainage. Two simulations of annual and seasonal water balance outputs for Ouagadougou on 10-day basis in a soil assumed to store 100 mm water in the root profile are presented. The use of AE_{max}IPE ratios (K factor in the model) for arriving at indices of crop moisture adequacy/stress in a stochastic model are discussed.

A Water-Balance Model

Rainfall is always erratic, even in humid regions. And even in arid regions an excess of water can be just as damaging to a crop as a deficit, particularly in the practice of supplemental irrigation. A water-balance model should be stochastic to account for the unpredictable nature of water resources. But a stochastic system would be poorly suited to 5-, 7-, or 10-day intervals, as the frequency distributions of rainfall are not independent for such short time intervals (a continuity effect is produced). And, moreover, to haphazardly generate rains on the basis of 73, 52, or 36 frequency distributions (over an entire year) — to overcome the continuity effect — would involve considerable effort.

If a water-balance program is to be of any real use, it should be as simple as possible. This would be the case with a deterministic model, which has the same uses as a stochastic model, provided the rainfall sample is sufficiently large. In this case, the statistical analysis is carried out on the output instead of the input.

This is how ORBVCR, the ORSTOM water-balance model suited to arid regions, was conceived. In these areas, the crop season begins on a soil whose profile has been more or less thoroughly dried out before the onset of the rains and will be receiving water progressively towards the lower horizons. To simulate this rewetting process, the soil is usually divided into layers that fill up rapidly — a procedure that is also very complicated. Compared to this type of model, the only originality of ORBVCR is that it uses an extremely simple system for simulating the progressive rewetting process.

ORBVCR uses Eagleman's (1971) formula to calculate actual evapotranspiration (AE). Designed for a relatively high level of technology in agriculture, the system predicts runoff only for the amount of heavy rainfall exceeding maximum water-holding capacity (K). It also enables the water-balance computation to be started on a fixed date or from a 5-, 7-, or 10-day period with a given rainfall total; this may or may not include the amount of water present at the beginning. On fixed dates, supplemental irrigation may be added to rainfall. The system is provided with control parameters so that it can be adjusted to observations of variations in soil moisture.

The Growing Period

The water-balance model is difficult to use because it provides elaborate and specialized information whose applicability is more limited than that of elementary information. In regard to simple rainfall levels, all hydrological prob-

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Note: This paper is an edited translation of the original French text, which appears in Appendix 1.

lems in agriculture will be encountered, at least initially. On the other hand, a water-balance program established for a cultivar with a definite growth period planted at a specific time on a soil with given hydrological characteristics will necessarily have a narrower application.

Nevertheless there is one solution that enables us to generalize the results from a simulation of balances established for a sufficiently long period of years, to all crops, soils, and cropping operations of a region covered by the same meteorological station. This solution is based on the concept of the "growing period."

This concept has the advantage of reducing the crop-weather relationship to a single comprehensive expression, which avoids difficulties arising from multiple probabilities. The "growing period" is the most comprehensive expression because it integrates all the factors involved in the production process. However, although this concept integrates these factors in a continuous fashion, its statistical analyses can only be discontinuous, focusing only a number of specific events.

Any climatic or phenological event is important for delineating the growing period in the annual cycle that meets the objective of a study. Consequently, there can be at the sametime as many different growing periods as there are specific projects. Nevertheless, it is possible to generalize this rational concept by considering climatic events that are valid for all cases; for example, the points where the potential evapotranspiration (PE) and rainfall (R) curves meet (Fig. 1). But above all, by expressing the concept in frequencies, it is possible to establish a risk level for any specific problem.

Probabilities in the growing period are shown by a system of coordinates where the x axis is time and the y axis the scale of relative frequencies. In this system the variability of each specific event characterizing the growing period can be shown (Fig. 2A):

- by a histogram frequencies—at 10-day intervals, for example,
- by a polygon of relative frequencies or a sigmoid curve of global probabilities if the sample is large enough to be representative of the general population.

Thus the growing period is marked off by frequency distributions (histograms and sigmoid curves); these taken in twos— successively or otherwise — determine the periods and subperiods. For example, taking events B (beginning) and E (end) of the period under study, sigmoid curve B gives the probability of its having already begun at any given date; and sigmoid curve E, the probability of its having already ended. But what interests us is the probability of it being still open; this will be given by symmetric sigmoid curve E (Fig. 2A). Symmetric sigmoid curves I (Fig. 2B) can also be constructed for intermediary events.

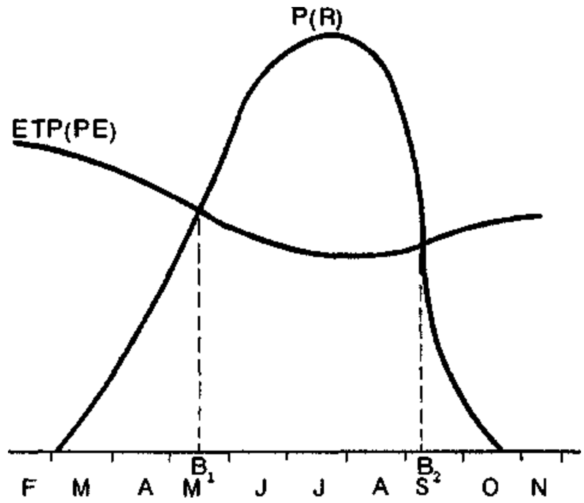

Figure 1. A generalized relationship between rainfall and potential evapotranspiration. (Letters in parentheses are for the English text)

The advantage of this geometrical model lies in its integration of the variability in the occurrence and duration of the growing period as established by the size and shape of the area bounded by the two sigmoid curves. First, it gives a "view" of all the possible growing periods with — if the events are either independent or have little correlation — the compound probability (product of two elementary probabilities) that the growing period would be ongoing between any two dates. This constitutes the statistical framework for all operations of the cropping calendar and their chances of success. The ability of a crop or cultivar to adapt to the conditions thus represented in relation to the timing of its cycle that offers the best probability is also shown by the size and shape of the area between the two sigmoid curves. Finally if, as in tropical regions, the model has

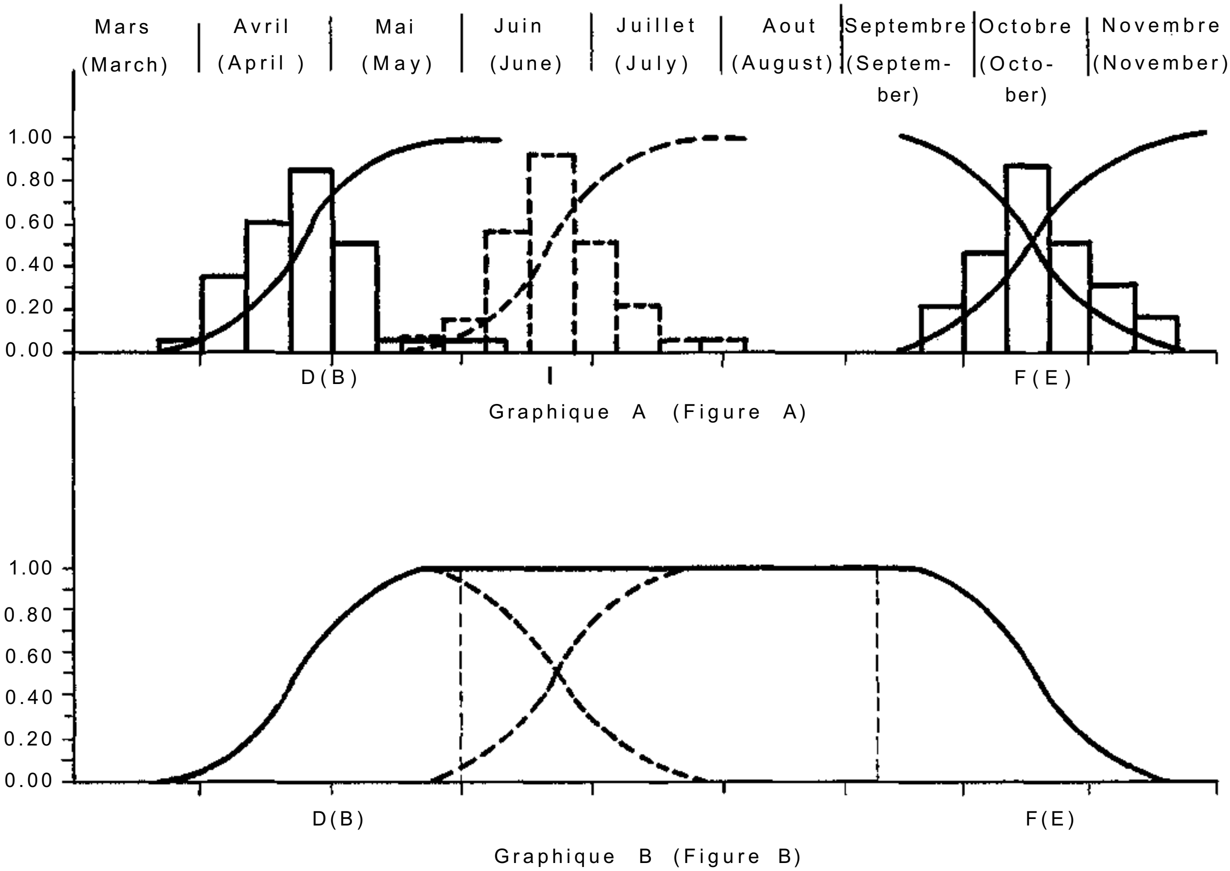

Figure 2A and B. Histograms showing the time and duration of a growing period. (Matter in parentheses is for the English text.)

been constructed in terms of the probability of rainfall exceeding PE (or PE/AE), the size of the area (which can be further weighted by a radiation factor of photosynthetic production) will show the dry-matter production capacity: this will be a relative climatic index of productivity.

Water-Balance and the Growing Period

This model can be constructed, in terms of water or energy, based entirely on elementary data such as rainfall or temperature levels or on more complete information such as *RIPE* values, or on very elaborate information such as the results of the simulation of water balances. As the water-balance model requires the definition of K (maximum plant-utilizable available soil water) soil characteristics determining the value of K for a crop may be included in the model to a certain extent. The model can be constructed for a given K once the balance model is adjusted to observed variations in soil moisture. But for wider application, it can also be constructed on the basis of several K values (for example, 50, 100, and 200 mm), so that the results can be interpolated for intermediary values of K (for example 80 or 130 mm).

Table 1 gives an example of simulation of the water-balance program for 1973 at Ouagadougou with a K of 100 mm. With such simulations for a sufficiently long period (at least 30 years), it is possible, depending on the requirements, to construct frequential models in terms of AE (actual evapotranspiration), PE-AE or Ep-AE (water deficit of a crop), SM (soil moisture), etc. But the AE/PE ratio (relative evapotranspiration) is of particular interest because it is an indication of water availability that linearly influences dry-matter production.

Table 1. Water balance output on 10-day basis for 1973 at Ouagadougou, Upper Votla.

Periods	Rainfall	Irri-gation	Surplus soil reserve	%Sur-plus	PE	Crop coeffi-cient	Maximum evapotranspi-ration (ME)	AE	Soil moisture	Runoff	Cumu-lative runoff	Soil water deficiency	Relative deficit	AE/PE	ME-AE	Available reserve[1]
Jun 1st	55.2	.0	55.2	1.00	69.0	.50	34.5	34.5	20.7	.0	.0	34.5	.62	.50	.0	55.2
Jun 2nd	7.5	.0	28.2	.51	64.0	.50	32.0	28.2	.0	.0	.0	55.2	1.00	.44	3.8	55.2
Jun 3rd	24.9	.0	24.9	.45	62.0	.55	34.1	24.9	.0	.0	.0	55.2	1.00	.40	9.2	55.2
Jul 1st	14.5	.0	14.5	.26	60.0	.60	36.0	14.5	.0	.0	.0	55.2	1.00	.24	21.5	55.2
Jul 2nd	49.5	.0	49.4	.89	58.0	.70	40.6	40.6	8.8	.0	.0	46.4	.84	.70	.0	55.2
Jul 3rd	214.5	.0	100.0	1.00	60.5	.85	51.4	51.4	48.6	123.3	123.0	51.4	.51	.85	.0	100.0
Aug 1st	44.2	.0	92.8	.93	53.0	1.00	53.0	52.1	40.7	.0	123.0	59.3	.59	.98	.9	100.0
Aug 2nd	84.2	.0	100.0	1.00	50.0	1.00	50.0	49.8	50.2	24.9	148.2	49.8	.50	1.00	.2	100.0
Aug 3rd	38.7	.0	88.9	.89	55.0	1.00	55.0	53.5	35.4	.0	148.2	64.6	.65	.97	1.5	100.0
Sep 1st	20.4	.0	55.8	.56	51.0	1.00	51.0	39.9	15.9	.0	148.2	84.1	.84	.78	11.1	100.0
Sep 2nd	34.4	.0	50.3	.50	51.0	1.00	51.0	37.4	12.9	.0	148.2	87.1	.87	.73	13.6	100.0
Sep 3rd	25.6	.0	38.5	.39	53.0	1.00	53.0	31.5	7.0	.0	148.2	93.0	.93	.59	21.5	100.0
Oct 1st	30.3	.0	37.3	.37	56.0	1.00	56.0	30.9	6.4	.0	148.2	93.6	.94	.55	25.1	100.0
Oct 2nd	.0	.0	6.4	.06	58.0	1.00	58.0	6.4	.0	.0	148.2	100.0	1.00	.11	51.6	100.0
Oct 3rd	1.4	.0	1.4	.01	61.6	1.00	61.6	1.4	.0	.0	148.2	100.0	1.00	.02	60.2	100.0
Nov 1st	.0	.0	.0	.00	53.0	1.00	53.0	.0	.0	.0	148.2	100.0	1.00	.00	53.0	100.0
Nov 2nd	.0	.0	.0	.00	51.0	1.00	51.0	.0	.0	.0	148.2	100.0	1.00	.00	51.0	100.0
Nov 3rd	.0	.0	.0	.00	50.0	1.00	50.0	.0	.0	.0	148.2	100.0	1.00	.00	50.0	100.0
Dec 1st	.0	.0	.0	.00	50.0	1.00	50.0	.0	.0	.0	148.2	100.0	1.00	.00	50.0	100.0
Dec 2nd	.0	.0	.0	.00	49.0	1.00	49.0	.0	.0	.0	148.2	100.0	1.00	.00	49.0	100.0
Dec 3rd	.0	.0	.0	.00	56.1	1.00	56.1	.0	.0	.0	148.2	100.0	1.00	.00	56.1	100.0
Total	645.2	.0			1171.2		1026.3	497.0							529.3	

1. Maximum available reserve = 100 mm
Water balance : total rainfall − total PE = −526.0 mm

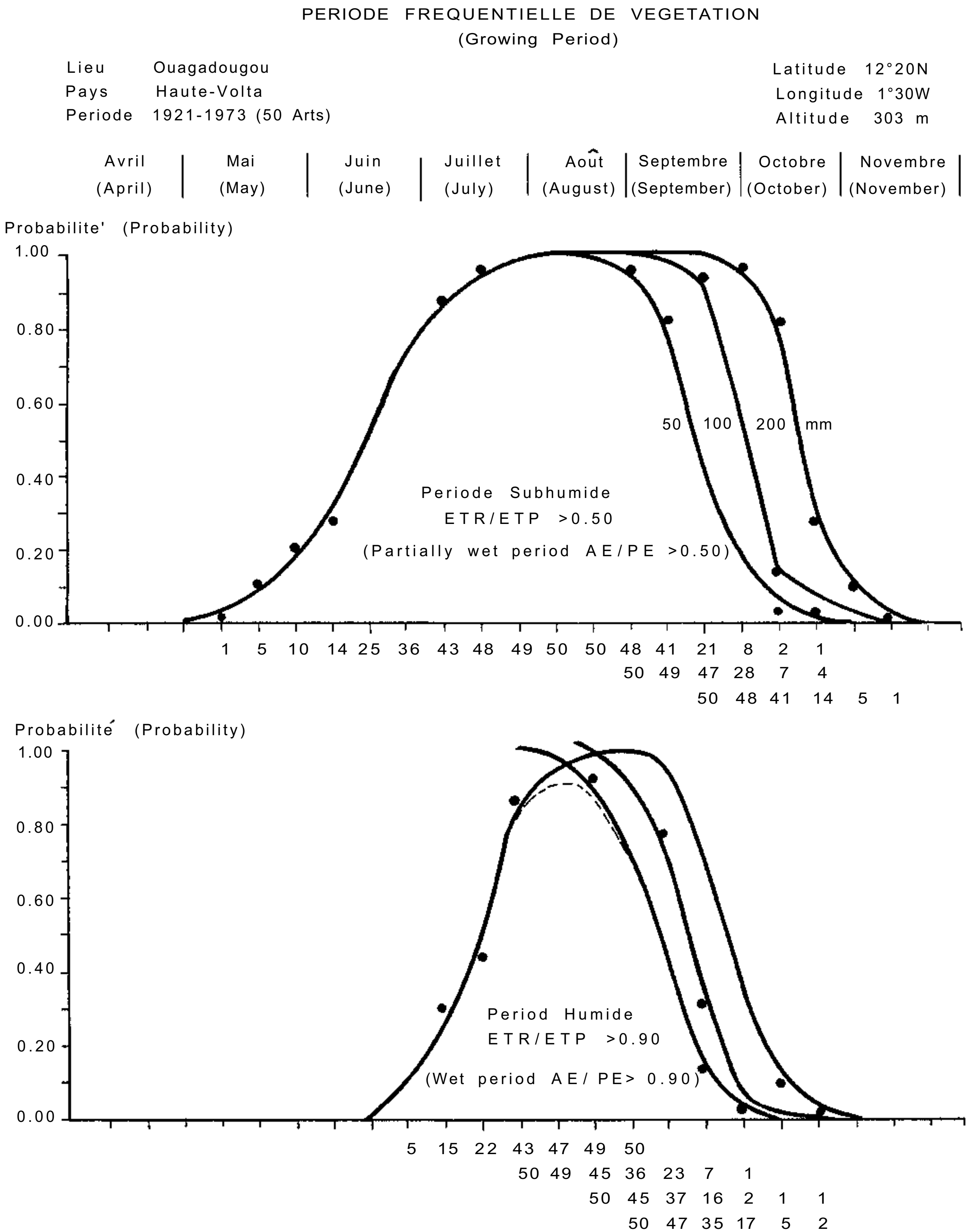

Figure 3. The probable length of the subhumid (ETRIETP>0.50) and humid periods (ETRI ETP>0.90) in three soils at Ouagadougou, Upper Volta from 1921 to 1973. (Matter in parentheses is for the English text.)

Generally, for annual crops (Gramineae, groundnut, cotton) only two levels of the AE/PE are considered. One is about 0.50 because this corresponds to the minimum conditions required for ensuring crop establishment (germination, emergence, seedling stage) and maturation. The other, about 1.00, corresponds to conditions required for seed development. Figure 3 is a frequential model of the growing period constructed for Ouagadougou:

- based on the probability of exceeding 0.50 (AE/PE). The beginning and ending sigmoids give in frequencies what can be called a semi-humid period for K: values of 50, 100, and 200, mm.
- for the probability of exceeding 0.90 (AE/PE). The sigmoids give the frequencies for what can be called the humid period forthe same values of K.

Between the ending sigmoids (the beginning sigmoids are practically the same regardless of the K), other sigmoids corresponding to intermediary K values can be interpolated.

For annual or perennial crops grown not for grain but for fodder, which is the direct product of dry-matter output, a larger number of AE/PE levels can be considered — 0.20, 0.40, 0.60, 0.80, 1.00, 1.20, etc.

Because this is a statistical model and it is therefore possible to fix climatic risk levels according to particular problems, this growing period model can be generalized to cover all crops, cropping operations, and soils of a region served by the same meteorological station.

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Water Requirements and Adaptations to the Rainy Season of Millet in Senegal

C. Dancette*

Summary

The water requirement of millet (Pennisetum typhoides) *was measured at CNRA (National Agricultural Research Center) in Bambey, Senegal, between 1973 and 1977. Varieties of 75-, 90-, and 120-day duration were tested. On the whole, water requirements are in direct proportion to the length of the growing period. It is not at all as simple to calculate grain and straw yields, especially the amount of water required to produce 1 kg of dry matter is considered. The results were interpreted with a view towards water economy and adaptation to marginal rainfall conditions. This paper is not restricted to a report of the results obtained, but attempts to generalize them for the whole of Senegal by characterizing the evaporative demand (particularly the north-south gradient).*

The water supply was studied not only under optimum conditions (with supplemental irrigation for measuring optimum water requirements, MET, but also under conditions of limited water supply; figures showing the effects of water stress on grain and straw yields are given whenever possible, depending on whenever rainfall conditions and the varieties permitted. Some descriptions of the work are given for practical use of the data at the research and development level.

Pearl millet (*Pennisetum typhoides*) is a staple food in Senegal, it is estimated that in theSerere region an average of 400 g of millet per day is needed per person (Bilquez 1975). Cultivated on more than 600 000 ha, millet gives very poor yields (average 520 kg/ha), whereas groundnut yields can easily exceed 1000 kg pods/ha or about 730 kg kernels/ha.

Although the incentive to grow millet in subsistence farming is high, commercially it does not pay at present (36 CFA francs or $0.17/kg grain for millet compared to 42 CFA francs S0.20/kg for higher-yielding groundnut on the official market in 1977). Yet it is still in the farmer's interestto improve millet yields, either to ensure self-sufficiency in food, or to devote larger areas to more profitable crops (groundnut, cotton, cowpea, etc.). A suitable price policy and improvement of millet production technology (storage, threshing, milling, use for making bread) would rapidly changethe millet situation to the advantage of both the farmer and the state.

On a purely agronomic level, millet yields can be increased through research efforts in breeding, cropping techniques, fertilization, and plant protection.

This paper discusses the water requirements of millet and the rational adaptation of this crop to the soil and rainfall conditions in Senegal. Data on optimum water requirements, or *maximum evapotranspiration* (MET) and on the response curve of millet to water stress during the growing period help us to better understand millet production. This enables a better choice of varieties, cropping techniques, etc., at the research and extension levels.

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Note: This paper is an edited translation of a paper in French (See Appendix 1) that was prepared for A. A. A. S. A. 3rd General Conference and 10th Anniversary, April 1978, Ibadan, Nigeria.

Water Requirements of Millet (MET) Measured at CNRA, Bambey

General Conditions

Between 1973 and 1977 the water requirements of millet were measured at CNRA, Bambey, in the central zone of Senegal. Varieties tested were of 75-, 90-, and 120-day duration.

The crops were grown in large plots of 196 m^2 (four replications) and under good agronomic conditions (heavy fertilization, plowing, plant protection treatments, protection against birds, etc.). The deep soil, locally known as Dior, was sandy, tropical ferruginous, and slightly leached.

Crop spacing was that recommended by research and extension specialists: 100 x 100 cm for 90-day Souna millet in 1973 and 1974; 50 x 20 cm in 1974, and 45 x 15 cm in 1975, for the 75-day GAM dwarf millet; 90 x 90 cm in 1976 and 100 x 100 cm in 1977 for the 120-day Sanio millet.

A supplemental irrigation was given with sectional angled sprinklers; applications of water were monitored by rain gauges installed just above the crop.

Water use was measured by two methods:

1. In situ, using 4-m deep access tubes and periodic readings (usually weekly) of soil moisture with French or American neutron probes provided by the International Atomic Energy Agency (IAEA), though French aid (special assistance from GERDAT), and by the Nuclear Energy Center in Cadarache, France. The soil at the start of each cropping season was dried out to the greatest possible depth. In 1976 and 1977, the flux was monitored by soil moisture tensiometers (IAEA aid) installed either vertically up to a depth of 150 cm, or horizontally 150 to 400 cm deep in a pit. Measurement of the water balance was facilitated by exceptionally poor rainfall so that the soil was not wetted to a great depth (<250 cm, usually <150 cm). Thus, the water balance could be easily controlled by nonexcessive irrigation without unchecked percolation or runoff (vertical protective plates around tubes).
2. In field lysimeters 4 m^2 and 1-m deep. The lysimeters, which were installed and monitored in 1972, had been considered as a possible alternative to the in situ water-balance method in case of excessive or even normal rainfall and percolation difficult to monitor. But on the whole, after a trial run of installation and monitoring, they did not give very different results from the first water-balance method, and after 5 years of deficit rainfall it even appears that we could have dispensed with the lysimeters. But this was not evident at the beginning and could be proved wrong by a more rainy season. Access tubes for neutron probes were installed in the middle of the lysimeters for the usual water-use measurements until natural gravitational drainage started. Actually, lysimeters should not be saturated right at the start of the crop to ensure proper drainage and normal water-balance measurement as it could lead to differences in methods and therefore in plant performance in relation to the rest of the plot.

Besides the MET method, there was also the AE (actual evapotranspiration) method without supplemental irrigation where the level of water stress attained would depend on the rains. This will be discussed later while dealing with the water requirements of millet.

Main results

We will only give a summary; other partial but detailed results relating to short-duration millet are given in another paper (Dancette 1975). The figures indicated in Table 1 are averages of four replications. Coefficients of variation are generally less than 10% for overall water use and for grain and strawyields (seeTable 5). Grain yields are sometimes less uniform than those of straw because damage by birds cannot always be completely avoided.

Annual Variations in Global PE for the Same Millet Variety

Year-to-year differences in the water requirements may be noted forthe same variety. Slight changes may certainly occur in cropping practices, rain distribution, irrigation and parasitism, but it is the evaporative demand that varies most of all. It is for this reason that the evaporative demand is estimated daily by measuring the potential evaporation from a free water surface in a standard class-A pan (WMO model) and it is related to the crop's water use for corresponding periods.

Thus, the evaporative demand was measured from 1972 through 1977 for periods of 75, 90, 105, and 120 days corresponding to the growing periods of the major crops. Data on the cumulative totals of pan evaporation in mm for these periods and, in parenthesis, an index of the evaporative demand in relation to the 1972-1977 averages are given in Table 2. Coefficients

Table 1. Main results for millet varieties of 75-to 120-day duration.

Crop	Year	Rainfall (mm)	Treatment	MET or water requirements (mm)	Yields (kg/ha) Grain	Rachis	Straw
					Moisture	content in	parentheses
Sanio millet 120 days (Maka strain)	1976	3999	Irrigated (MET) i = 215 mm	562 K = 0.75[1]	2035 (7.5%)	1426 (10.1%)	13 950 (3.2%)
Sanio millet 120 days (Bambey strain)	1977	374	Irrigated (MET) i = 283 mm	628 K = 0.77	1623 (3.5%)	1388 (4.0%)	14 425 (7.5%)
Souna millet III 90 days	1973	400	Irrigated (MET) i = 68 mm	417 K =0.72	2690 (7.8%)	1360 (7.8%)	6 680 (4.3%)
Souna millet III 90 days	1974	492	Irrigated (MET) i = 73 mm	416 K =0.74	2948 (5.4%)	1600 (5.4%)	5 760 (5.2%)
GAM millet 75 days	1974	447	Irrigated (MET) i = 51 mm	320 K = 0.67	2151 (9.0%)	2165 (9.0%)	5 943 (8.4%)
GAM millet 75 days (cereal crop structure)	1974	510	Nonirrigated (excess rain) AE = MET	327 K = 0.63	1721 (9.2%)	1395 (9.2%)	5 652 (10.2%)

1. $K = \frac{MET}{E_p}$

Table 2. Cumulated class-A open pan evaporation (in mm) at Bambey

Period	Year 1972	1973	1974	1975	1976	1977	1972-77 average
75 days	550 (1.12)	486 (0.99)	477 (0.98)	438 (0.90)	489 (1.00)	496 (1.01)	489
90 days	631 (1.10)	583 (1.02)	564 (0.99)	523 (0.91)	560 (0.98)	573 (1.00)	572
105 days	722 (1.06)	702 (1.03)	695 (1.02)	620 (0.91)	648 (0.95)	687 (1.01)	679
120 days	811 (1.03)	817 (1.04)	809 (1.03)	714 (0.91)	744 (0.95)	812 (1.03)	785
Date of first effective rainfall	5 June	2 July	12 July	7 July	13 July	7 July	

of variation range from 5% for 120 days to 7% for 75 days.

Pan evaporation should be taken as reference for any comparison. If the two 120-day Sanio millet crops are compared in this way, it will be observed that the water requirements were:

in 1976, 562 mm for 774 mm of pan evaporation with a 0.95 index
in 1977, 628 mm for 812 mm of pan evaporation with a 1.03 index

However, the seasonal coefficient K = MET/Ep was close to 0.75 in 1976 and 0.77 in 1977. By relating this to the average evaporative demand (1972-1977) and to the index 1.00, we find the water requirements to be:

$$\frac{562}{0.95} = 592 \text{ mm in 1976 and } \frac{628}{1.03} = 610 \text{ mm in 1977}$$

The results are quite similar with differences that are well below any possible experimental errors — water requirements measured roughly at ± 8% when maximum precautions are taken.

Although year-to-year variations in evaporative demand are of this order and even less, it is not an adequate reason for not taking it into consideration whenever possible. Thus, the seasonal water requirement can be assessed by relating it to the average evaporative demand (1972-1977):

- 120-day Sanio millet: average of 592 and 610 mm, about 600 mm.
- 90-day Souna millet: average of 4.17/1.02 = 409 and 416/0.99 = 420, about 415 mm.
- 75-day dwarf millet: The deviations are slightly greater, as plant material had been changed between 1974 and 1975 and a composite with slightly different architecture (cereal type) was adopted.

Nevertheless, the average of 320/0.98 = 327 and 327/0.90 = 363, 345 mm may be used.

Similarly, the extremes can be characterized according tothe highest and lowest evaporative demands recorded over the last 6 years. The figures shown in Table 3 will be retained until a longer observation period is available. This is also shown in graphic form in Figure 1.

Table 3. Variations in global water requirements of millet according to the growing period and the evaporative demand at CNRA, Bambey. (See also Fig. 1.)

Crop	Minimum MET	Average MET	Maximum MET
120-day Sanio millet	546	600	624
90-day Souna millet	378	415	457
75-day dwarf millet	311	345	386

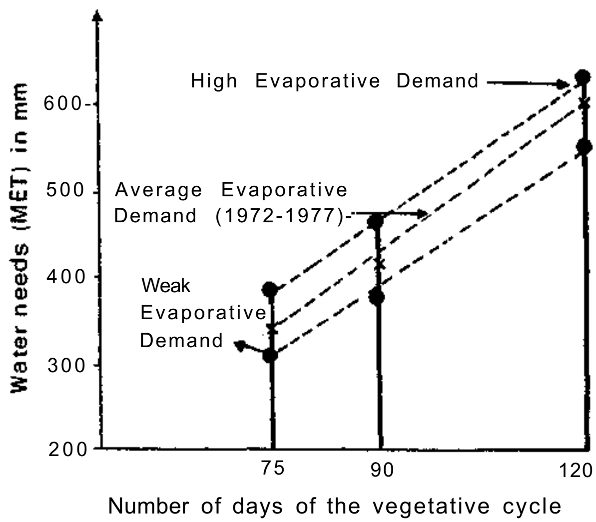


Figure 1. Variations in global water requirements of millet according to the growing period and evaporative demand at CNRA, Bambey, Senegal.

Variations in MET of Millet and in Crop Factors, K, throughout the Same Crop Duration

The evaporative demand varies throughout the rainy season: very high at the beginning (pan evaporation up to 8 mm/day in June at Bambey), it then decreases once the rains set in and surrounding humidity increases (4-4.5 mm/day in Sept.); and rises again with the withdrawal of the rains (7-8 mm in Oct.). Abnormal droughts during the rainy season may cause it to fluctuate abruptly.

Water requirements vary according to the extent and rapidity of the crop cover over bare soil at the beginning of the cropping season. Thus, very early varieties (accelerated growth and development) or those with high plant density cover soil more rapidly than others and require more water. These water requirements also decrease as the crop matures, which may coincide with a low evaporative demand in the middle of the rainy season for a very *early* variety (75 days) or an increasing evaporative demand at the end of the rainy season for a variety with longer duration (120 days).

It is for this reason that once again water requirements should be expressed in terms of the evaporative demand (standard class-A open pan) and the coefficients $K = MET/E_P$ should be calculated forthe entire duration. This was done for all three millet varieties over successive 15-day periods; the results are shown in Table 4. Since each type of millet was tested over at least 2 successive years, the K coefficients were compared and an average representative value was retained.

Figure 2, in which only the representative values of K are used, clearly shows the difference between the three millet types. The maximum values obtained for K are:

1.20 for Sanio millet; 1.10 for Souna millet; 0.97 for GAM millet.

Likewise, in Table 1 the seasonal K coefficients were: 0.76 for Sanio millet, 0.73 for Souna millet, and 0.65 for GAM millet. It seems that these two facts are linked to the respective heights of these millets: Sanio millets are very tall (> 3.5 m), Souna millets *are of medium* height (2-2.5 m), and dwarf millets are about 1.0 m. Moreover, whereas the soil surface in a Sanio millet field is *very irregular* (in waves), that of Souna millet and specially of GAM millet is much more homogenous. All these factors undoubtedly make the energy advections much higherforthe Sanio than for the other crops and the water needs are also increased. However, there is no evidence thatthe same results will be obtained in very large plots (> 1 ha) where advections are probably reduced. Actually, this raises the problem of the scale of agroclimatic characterization: small plot, field, or ecological zone? But it is also possible that these differences might actually be linked to the physiology or the architecture of the test varieties; this remains to be demonstrated. Perhaps the correct solution lies between these different theories.

The three varieties can be compared (Fig. 3) on the basis of the average values of K and the 1972-1977 average of pan evaporation taken over successive 15-day periods right from the start of the cropping season. This comparison

Table 4. Changes in $K = \frac{MET}{E_p}$ during growth of 75-, 90-, and 120-day millet varieties.

	Sanio millet 120 days			Souna millet 90 days			GAM dwarf millet 75 days		
Days	1976	1977	Value retained	1973	1974	Value retained	1974	1975	Value retained
0-15	0.15	0.30	0.23	0.26	0.38	0.32	0.44	0.49	0.47
15-30	0.35	0.44	0.40	0.49	0.66	0.58	0.61	0.80	0.71
0-30	0.25	0.37	0.31	0.38	0.52	0.45	0.53	0.65	0.59
30-45	0.77	0.70	0.74	1.09	1.01	1.05	0.84	1.10	0.97
45-60	1.07	0.99	1.03	1.26	0.94	1.10	0.79	0.65	0.72
30-60	0.92	0.84	0.88	1.18	0.98	1.08	0.82	0.88	0.85
60-75	1.12	1.24	1.18	0.98	0.82	0.90	0.75	0.80	0.77
75-90	1.24	1.15	1.20	0.72	0.65	0.69			
60-90	1.18	1.20	1.19	0.85	0.74	0.80			
90-105	1.09	0.94	1.02						
105-120	0.71	0.82	0.77						
90-120	0.90	0.88	0.89						

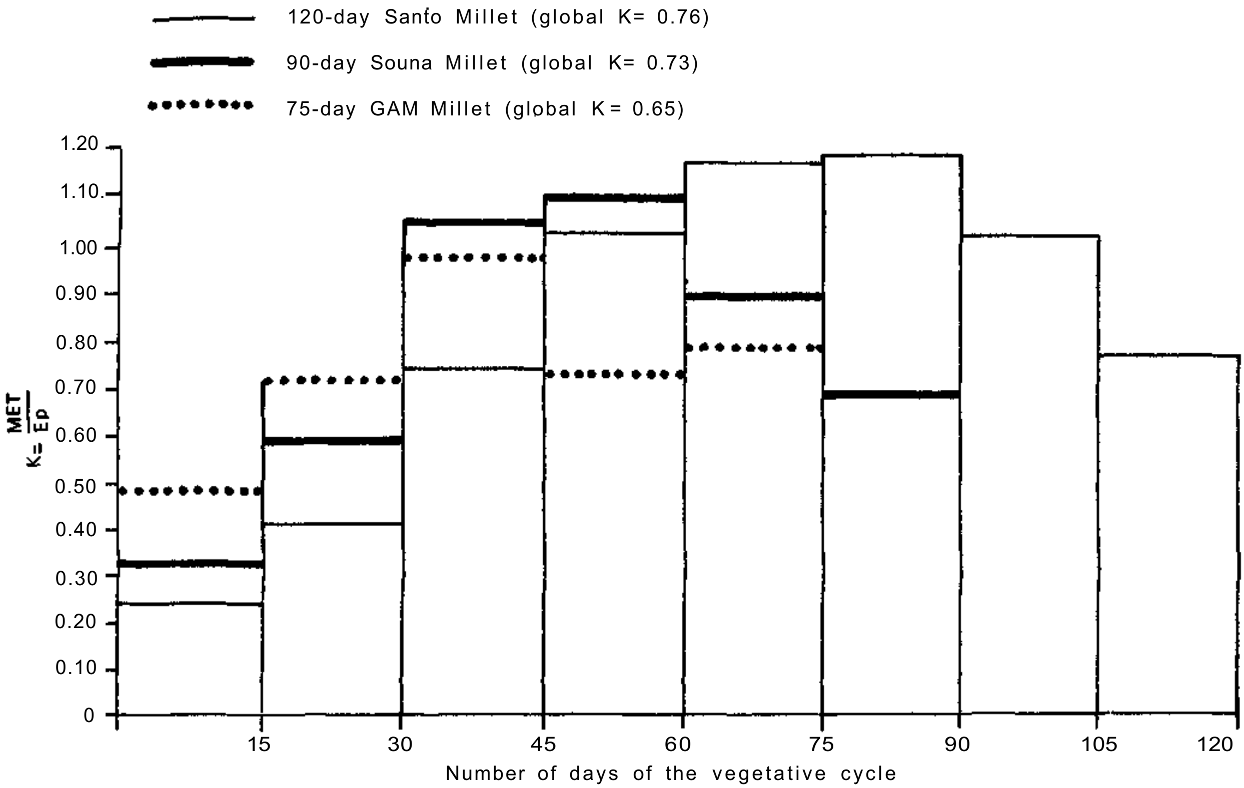


Figure 2. Changes in the K = METlEp coefficients during crop duration of three millet varieties of 75-, 90-, and 120-day duration.

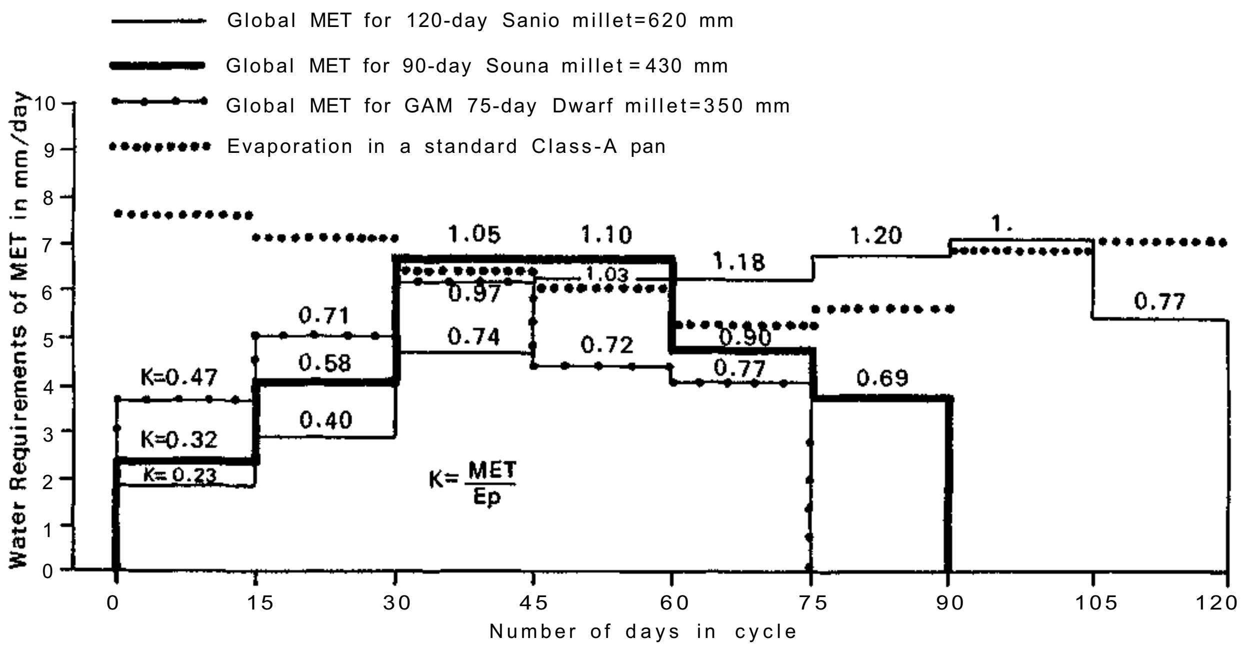


Figure 3. Comparative water requirements of three millet varieties at Bambey, expressed as average evaporative demand (Bambey, Senegal, 1972-1977).

clearly shows that water requirements are high at the start of the cropping season for short-duration varieties and at the end for the long-duration varieties.

Application of the Results to the Senegal Situation

Method

In Senegal, the evaporative demand varies from north to south and even from the coast inwards. It is high towards the north and low towards the south; it also increases towards the interior. This evaporative demand is related to humidity in the zone, that is, to rainfall, the main humidification factor.

The northward movement of the Inter-Tropical Convergence Zone brings a mass of humid air causing the rains to set in and wet the soil. Vegetation begins to cover the soil and the evapotranspiration from the crops, along with the typical rainy-season conditions (decrease in hours of sunshine and temperatures, increase in relative humidity, reduced wind velocity) contribute to reduced evaporative demand.

We were able to establish some negative correlations between the amount of rainfall received and potential evapotranspiration measured on turf (Dancette 1973) and between rainfall and potential pan evaporation (Dancette 1977). This enabled characterization by location of the evaporative demand during the rainy season. This was essential for the work on adaptation of rainfed crops, based on the application throughout the country of water requirement measurements. For this, there is already a relatively dense network of rainfall stations, unlike the network for evaporation measurement.

The relationship between rainfall and pan evaporation is established on a monthly basis for the entire rainy season:

$$E_p = A - BX - CY + DZ$$

where X is the rainfall for the month or season being studied

Y is the average annual rainfall at the station (latitude)

Z is the distance of the station from the coast (longitude)

This kind of equation is determined for transitional months (beginning of the rainy season), peak rainy-season months, or an entire period when rainfall is likely to occur (June-Oct); the correlation coefficients for these periods were 0.73, 0.78, and 0.86 respectively.

There is a simpler type of equation for the 5 months of the rainy season:

$$E_p = 10.4 - 2.76 \text{ Ln } R \quad (r = 0.92)$$

where E_p is the average pan evaporation in mm/day for the 5 months considered, and R is the average daily rainfall during the same period.

From these relations we can establish the following type of map for characterizing by location the evaporative demand (shown by evaporation in a standard class-A pan) during the rainy season in Senegal. The average evaporation is given in mm/day (June-Oct) and in parentheses is the index based on the observation at the Bambey station where water requirements of millet were measured (Fig. 4).

Limitations

Several points can be disputed such as:

- The variability in monthly rainfall in this area: Rainfall may occur either at the beginning or the end of the month without being well distributed throughout the month. Rainfall in a given month may influence conditions in the following month as a result of soil water reserves, etc.;
- The choice of a total period of 5 months: whether these 5 months are retained, or the exact period between the first "effective" rainfall and the end of the rainy season (last rain + period during which soil moisture reserves are used), or the number of whole months with significant rainfall, the equations hardly differ and, in our opinion, do not justify complicating the calculations any further.

The most crucial problem is to know which period should be retained for characterizing the evaporative demand. In 1973, we considered a long period (1931-1965) for determining the relationship between rainfall and PE during the

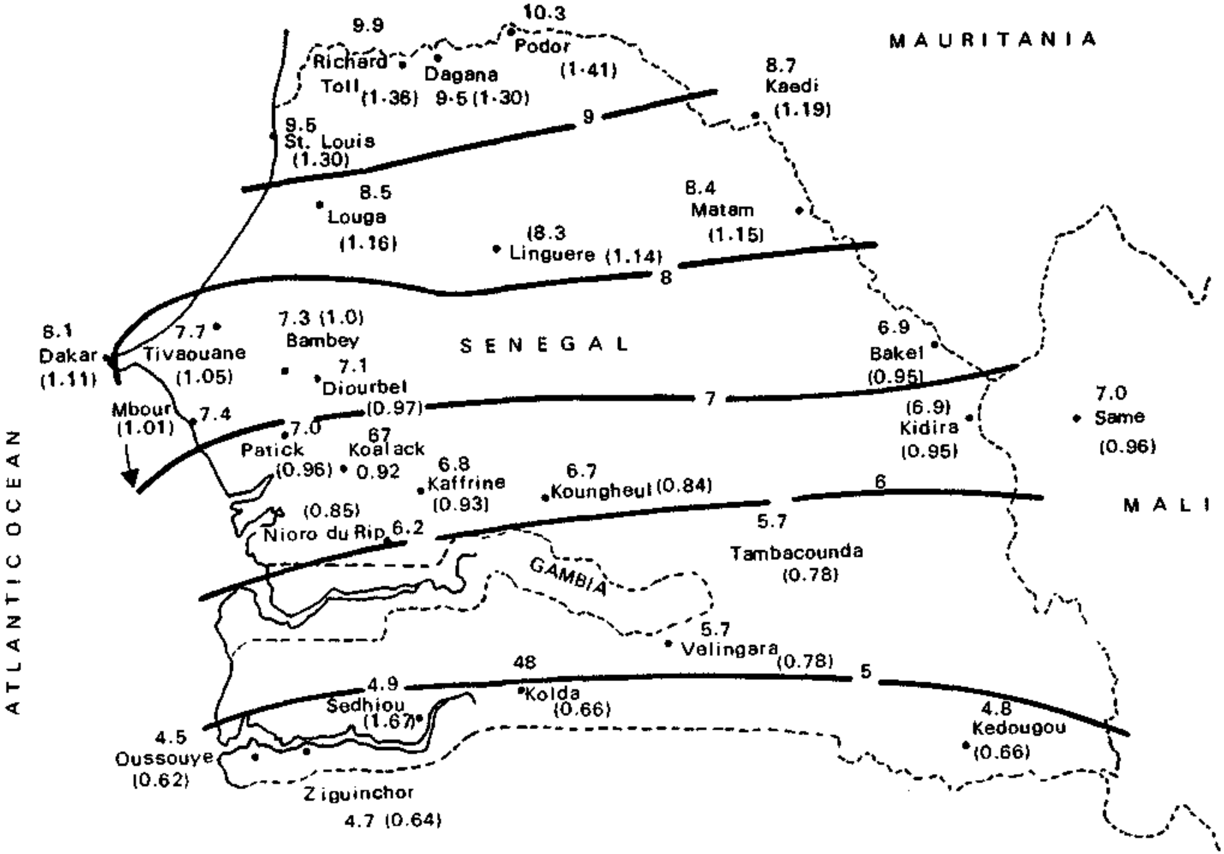


Figure 4. Variations in evaporative demand (mmlday) during the rainy season in Senegal (June-Oct), 1971-1976.

effective rainy season, as well as for the PE map. This greatly reduced the evaporative demand gradient — roughly 1.20 to the extreme north of the country and 0.80 to the extreme south, compared with Bambey.

On the other hand, between 1971 and 1976, a severe drought occurred when the network of standard class-A pans was being set up and extended. The rainfall-pan evaporation equation could not be applied to the 1931-1976 period. This equation needs to be corroborated by evaporation and rainfall readings over a long period. However, it is characteristic of years of deficit rainfall and an abnormally high evaporative demand.

Thus, the map showing the evaporative demand and its north-south gradient indicates some indices which are this time between 1.40 to the north and 0.65 to the south of Bambey, Senegal. However, the work should be aimed at adapting crops to the unfavorable conditions of the last 10 years, as it is easier to adapt them to better conditions.

- Use of the evaporative demand map and indices based on observations taken in Bambey.

According to this map, a 120-day millet requiring an average620 mm at Bambey, would need:

620 x 0.82 = 530 mm at Nioro-du-Rip
and 620 x 0.67 = 420 mm at Sefa.

In the same way, a 75-day millet requiring 350 mm at Bambey, would require:

350 x 1.16 = 410 mm at Louga
and 350 x 1.30 = 460 mm near Dagana.

Some Comments and Applications

Potentialities of Existing Millet Varieties in Central Senegal

Table 5 shows that the best grain yields are

Table 5. Water consumption and millet yields.

Crop	Year	Rainfall (mm)	Treatment	Evapotranspiration (mm)	Yields (kg/ha) Grain	Yields (kg/ha) Straw	Water requirements (liters/kg) Dry grain	Water requirements (liters/kg) Total above-ground dry matter[a]	Water requirement satisfaction rate (%)
Sanio millet	1976	399	Irrigated 215 mm	562 C.V. 6%	2035 (7.5) C.V. 7%[b]	13 940 (3.2) C.V. 11%	2 986	337	100
			Non-irrigated	403 C.V. 3%	1092 (7.4) C.V. 16%	10 478 (2.2) C.V. 10%	4 045	334	72
Sanio millet	1977	374	Irrigated 283 mm	628 C.V. 4%	1623 (3.5)[c] C.V. 8%	14 425 (7.5) C.V. 4%	4 010	387	100
			Non-irrigated	397 C.V. 4%	153 (3.5) C.V. 71%	11 172 (8.5) C.V. 14%	26 890	364	63
Souna millet	1973	400	Irrigated 68 mm	417 C.V. 3%	2690 (7.8) C.V. 5%	6 680 (4.3) C.V. 7%	1 681	412	100
			Non-irrigated	378 C.V. 3%	2770 (7.8) C.V. 3%	6 240 (4.3) C.V. 6%	1 443	383	91
Souna millet	1974	492	Irrigated 73 mm	416 C.V. 7%	2948 (5.4) C.V. 3%	5 760 (5.2) C.V. 4%	1 492	426	100
			Non-irrigated	415 C.V. 8%	2951 (5.2) C.V. 2%	5 590 (5.1) C.V. 8%	1 483	434	100
GAM millet	1974[d]	447	Irrigated 51 mm	320	2151 (9.0)	5 943 (8.4)	1 635	342	100
			Non-irrigated	324	2288 (8.3)	5 780 (8.4)	1 544	350	100
GAM millet	1975	510	Non-irrigated (sufficient rain)	327 C.V. 6%	1721 (9.2) C.V. 12%	5 652 (10.2) C.V. 10%	2 093	414	100

a. Humidity is given in parentheses, the coefficient of variation (C.V.) is given below.
b. Above-ground dry matter includes straw, grain, sheath, and rachis.
c. Only three plots out of four were observed (retained for calculations).
d. In 1974, for the GAM millet experiment, measurement points were increased from two to five at the end of the season, so a statistical analysis was not possible.

obtained from the 90-day Souna millet (nearly 3 t/ha). The 75-day GAM millet undergoing varietal improvement already gives the same grain yields as 120-day Sanio millet (which is being completely abandoned in the Diourbel region). Souna millet yields a maximum of 2 tonnes, consuming nearly twice as much water as the GAM millet.

If water use by millet was expressed in terms of liters of water consumed by the plant and the quantity required to produce 1 kg of grain, there is little difference between the Souna and GAM millets. The situation is much worse for Sanio millet (3000-4000 liters/kg grain compared to 1500-1600 liters for the other millets).

Sanio millet has a high production potential for straw — about 14 mt/ha, or more than double that of Souna and GAM millets. Average water requirements to produce 1 kg of straw is:

- 440 liters of water for irrigated Sanio millet (average of 1976 and 1977)
- 616 liters of water for GAM millet (average of 1974 and 1975)
- 707 liters of waterfor irrigated Souna millet (average of 1973 and 1974)

Straw yields of the 75-day dwarf millet and Souna millet are comparable but dwarf millet matures in 75 days instead of 90 for Souna millet.

This aspect of "straw production" cannot be neglected, considering its increasing use for livestock feed, manure production, and in the house for roofs, enclosures, fuel, etc.

Although the 120-day Sanio millet should be rejected because of its poor grain yield potential and excessive water consumption, the abandoning of Sanio millet in the Diourbel region may possibly have contributed to the increasing shortage of straw on farms (one of the present constraints to development of sedentary livestock raising); the same situation occurs when there is a switch from 120-day to 90-day groundnuts. The "stabilization" of grain yields is not too compatible with high straw production.

Influence of Water Stress on Millet Production

The Souna and GAM millets, which, on the whole, are quite well suited to the water conditions in the Bambey region, were not subjected to any real stress during the years of experimentation, even though it was a period of deficit rainfall. Thus, in 1973, satisfaction of the water requirements of the non-irrigated Souna millet was 91% and its grain and straw yields differed very slightly from those of millet with supplemental irrigation. For the other years, supplemental irrigation did not increase yields of either Souna or GAM millet. Duc (1977) obtained somewhat similar results with Souna millet on the farm at Bambey during the rainy season; supplemental irrigation is especially effective further north. In central Senegal, there are other ways of stabilizing millet production besides irrigation, particularly through dryfarming techniques with year-to-year carryover of soil moisture reserves (Chopart and Nicou 1976).

On the other hand, differences between irrigated and nonirrigated plots were very great for Sanio millet which has adapted very poorly to these dry years (470 mm of rain at Bambey during these last 10 years instead of 640 mm during 1921-76). Yields of Sanio millet — for which water requirement was satisfied up to 72% in 1976 — dropped by 46% for grain and by 25% for straw. Yields of Sanio Millet — whose water requirement was satisfied up to 63% in 1977—fell from 1623 to 153 kg/ha, a decrease of 91%. Straw yields were less affected, since they fell by only 23%.

Flowering for irrigated millet was on:

- 2 Oct (82 days after planting) in 1976, at mid-heading stage
- 7 Oct (92 days after planting) in 1977 (more widespread flowering).

Water stress during the 20 days around these dates can be calculated as

$$\frac{\text{MET - AE}}{\text{MET}}\ \% = \frac{5.8 - 4.7}{5.8} = 20\% \text{ in 1976,}$$

corresponding to a 46% fall in grain yield

and $\frac{6.5 - 2.9}{6.5}\% = 55\%$ in 1977, corresponding to a 91% fall in grain yield.

Therefore, particular attention should be paid to stress at heading ratherthan throughout crop duration.

In the absence of a true test (response curve to water during the rainy season), which requires detachable covers or perfectly airconditioned greenhouses, we tried to approximate this curve by using results of various agricultural experiments in Bambey and other stations. Water consumption was measured by an in situ water balance, or it was combined with effective rainfall when rainfall was relatively well distributed (therefore, stored in the soil at a depth where it was available to the roots) and clearly less than crop requirement. Thus, at this first stage of the investigation we were able to obtain a technically good water response curve for 90-day Souna millet for the central zone (Thies, Bambey, Diourbel) (Fig. 5).

The same work will be carried out for 75-day and 120-day millets at the station and in farmers' fields. As this type of investigation separates technical and climatic factors, it also provides a better explanation of production and a more objective evaluation of the impact of agricultural extension efforts.

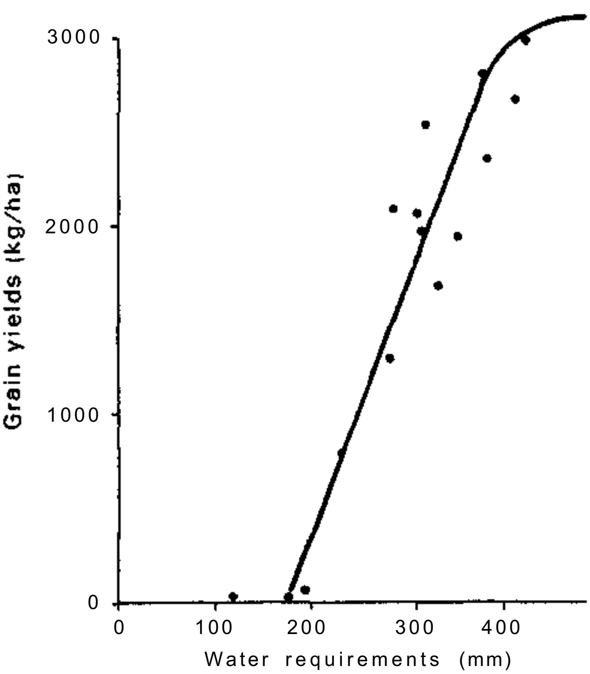
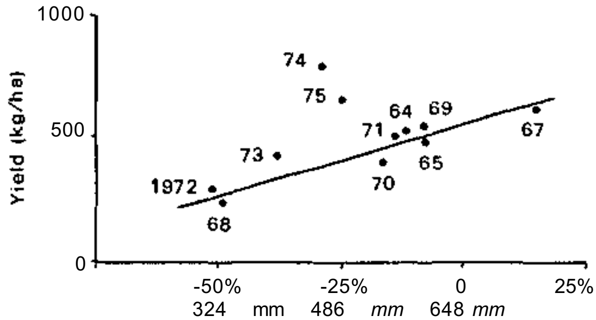


Figure 5. Water response curve for 90-day Souna millet crop with proper cultivation, fertilization, and maintenance (ISRA stations and PAPEM, North Central region).

Figure 6 is a first attempt in this direction; but it does not differentiate between 90- and 120-day millets and sorghum, and yield estimates are unreliable. Whatever the exact value of the figures, there is some logic in the trends — the effect of the severe droughts of 1968 (the worst drought recorded in 50 years), 1972, and 1973 and perhaps an upward trend in millet yields in 1974 and 1975 — which needs to be confirmed. This may be because sorghum and 120-day millet were almost completely abandoned in the zone studied; other reasons could be a change in the method of estimation by DGPA or improved technology (thinning, fertilization, etc.). It is useful both for research and for extension activities to better understand production mechanisms in order to provide better guidelines for future work.

Production ratio to cropped surface
in the Bambey administrative department.



Shortage or excess of rain in relation to the normal amount of rain during the cropping season

Figure 6. Changes in millet and sorghum and millet yields in farmers' fields in the Bambey Department (DGPA estimates).

Maps of Adaptation of Millet to Rainfall Conditions

This point was discussed in a paper for the IAEA Consultative Committee in 1975 at Bambey (Dancette 1975). This paper concerned 75- and 90-day short duration millets in the northern half of Senegal. This work should be extended to cover the entire country and should also include 120-day Saniomilletsforthecentral and southern parts of the country.

In 1975, the evaporative demand gradient had been calculated from a PE map for the period 1931-1965 (rainfall-PE correlation); the results would be even more negative if the evaporative demand over the last 10 years was based on rainfall-pan evaporation correlations.

The method is based on a study of the effective rainy season for a dry-sown millet crop and a comparison of the rainfall received and stored in the soil (to a maximum of 100 mm) with the water requirements of millet estimated at - 10% during cropping. Therefore, the length of the effective rainy season must be considered along with the satisfaction of the water requirements in order to know in retrospect if each year at a station had been favorable in terms of water supply. This requires detailed analysis of 40 years' data per station and a study of all the stations having a relatively long and complete series of observations and which are also well distributed throughout the area. The map in Figure7 gives an idea of the information that can be obtained. In the region represented by the shaded area, the change from a 90-day variety (Souna) to a 75-day variety (GAM dwarf) increases reliability of yields (80% and more chances of success).

Study of the Cropping Season and an Explanation of Production Mechanisms

In 1977 (Dancette 1977), a very general study was undertaken of the cropping season. It mainly focused on millet, groundnut, and cowpea, as their water requirements are similar for the same crop durations. Water requirements of these crops are in direct proportion to the length of the growing season (Fig. 8). It is also possible to plot on a graph the cumulated

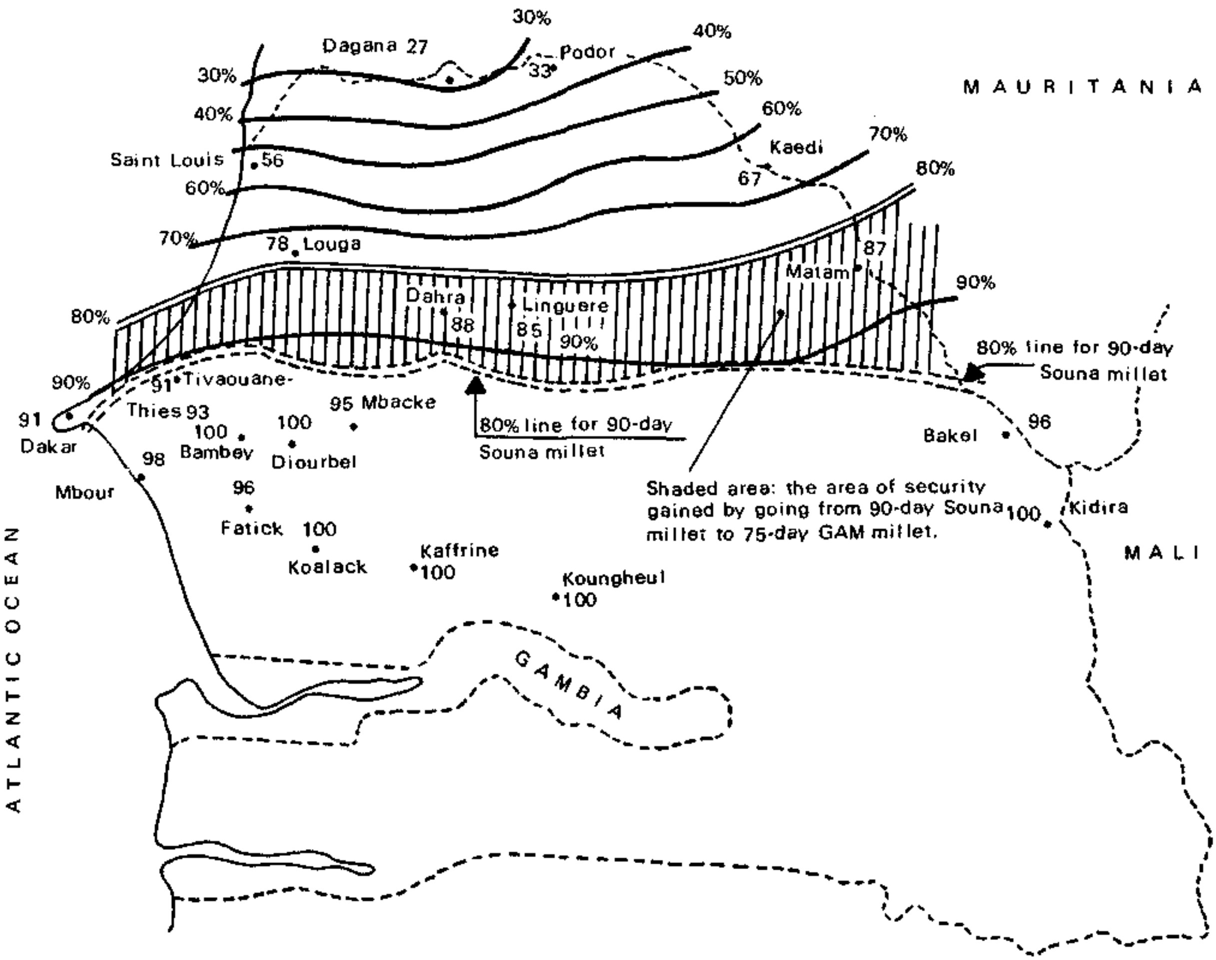


Figure 7. Lines of equal probability for favorable water conditions for a 75-day GAM millet.

curves for water requirements and rainfall from the day of the first effective rainfall (Fig. 9). This rainfall enables thedry-sown millet crop to start growing. The ideal would be to translate this curve of water requirements along the x axis (days) and also to fit it along the y axis in case of replanting or delayed planting.

Actually, in these cases, either the crop starts with an initial water content that can be estimated, or all the rain is lost (through evaporation) and the water requirements curve must be started from the cumulative rainfall level (the case of Thies in 1977). Finally, in certain exceptional cases (research stations), there may be an initial water content due to dry farming techniques (for example, postharvest cultivation). This should be taken into account by lowering the starting point of the water requirements curve in relation to rainfall.

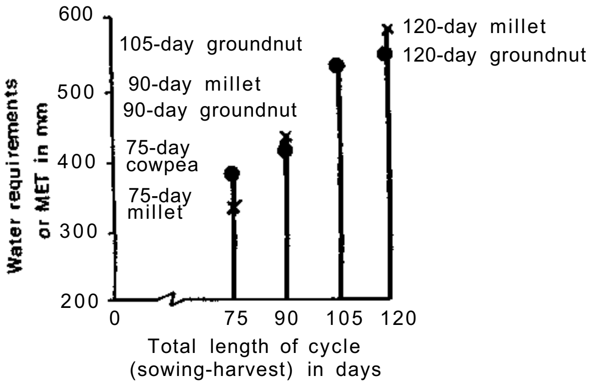


Figure 8. Water requirements of crops in Senegal are in proportion to the growing period.

The actual millet crop study would only need the specific water requirement data given earlier and an index, including the evaporative demand gradient, for each station. This gives an idea of the stress periods, their intensity, and possible effects on yields (by also using water response curves). In the case of Thies, taken from 25 other cases studied in 1977, cropping started exceptionally late and rainfall was very poor. If runoff and percolation were negligible and all the rain could be stored in the soil and used by the crop, only the 75-day varieties had some chance of success (76% satisfaction water requirement). The 90-day millet varieties had already begun to be affected at heading (about 60 days after planting) with only 62% satisfaction of total water requirement (A'B'/A'C, Fig. 9).

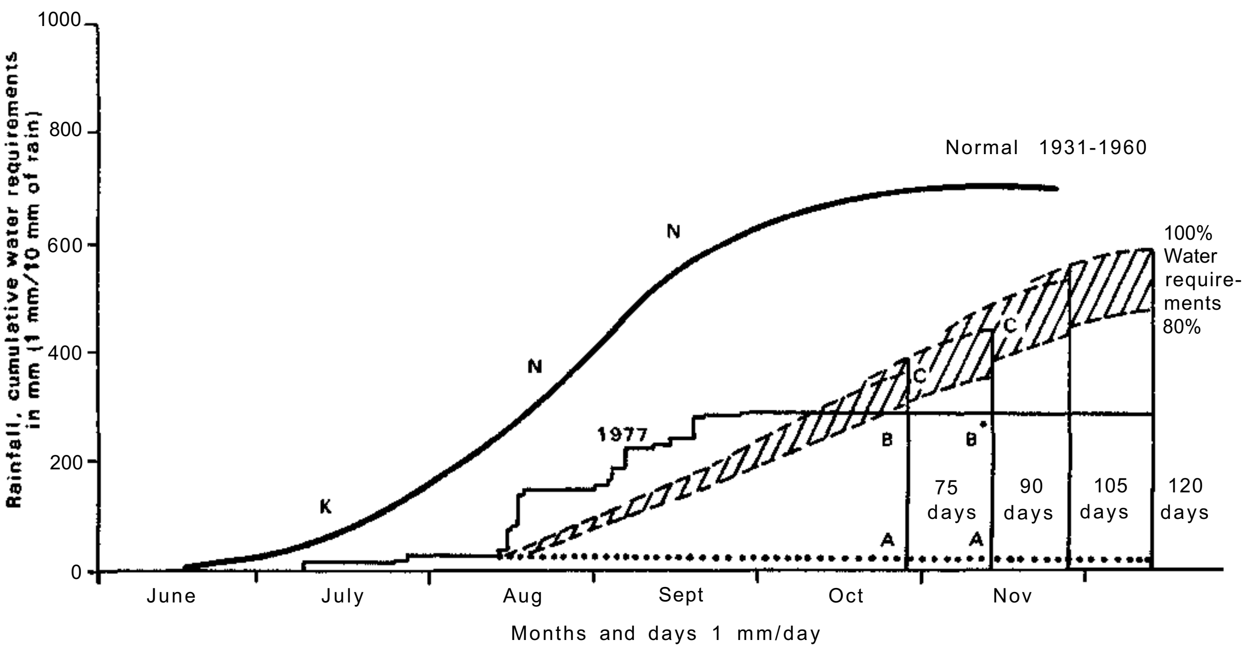


Figure 9. The 1977 rainy season (Thies meteorological station). Three dry-sown millet reseedings; sowing rain on 14 August: 52 mm; average date of last rain: 5 October.

Conclusion

The measurement of water requirement is a prerequisite to any work on the adaptation of cropsto a given pedoclimatic environment. The water requirements of millet grown under proper conditions are now known but not much is known about the requirement of a poorly cultivated millet crop with inadequate mineral nutrition. However, it is normal that research aims to obtain high yields and, therefore, adaptation of plants with relatively higher water requirements rather than stunted plants. Straw production should also be carefully considered forforms integrating livestock raising and other needs.

It is for these various reasons that, now more than ever (previously there were mediocre but perhaps more flexible varieties), criteria for varietal selection and determination (based on soil and rainfall data) of areas for promoting the main varieties should be exact. This approach has been adopted in Senegal by the Millet Improvement Group (GAM) whose work in selection and development of varieties is conducted in collaboration with agronomists and agroeconomists. The agroeconomists are able to specify what the farmers really want, how they use agricultural produce and by-products, and what constraints they face (weather, equipment, marketing, etc.). The agronomists can specify how these constraints can be alleviated (rainfall, soil cultivation, manure and organic matter) and which crops are most suited to overcome various agronomic problems.

Breeders and physiologists can thus direct their efforts towards specific objectives and meet the needs for development, even if these needs are not always as clearly defined as they should be, or if they change too rapidly. Thus large-scale development of sedentary livestock raising and summer fattening seems incompatible with the practice of incorporating crop residue as recommended previously. At the sametime, soilfertility should be maintained by applications of manure; methods of making and spreading manure need to be studied further.

All this requires careful attention and a combined effort involving large multidisciplinary teams for planned and specific regional operations such as, for example, increase of millet production to ensure self-sufficiency in food for a given ecological zone covering one or several administrative regions.

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Modeling Evapotranspiration

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Summary

Several reviews of evapotranspiration models are already available and in this presentation emphasis has been given to the Penman-Monteith model, the Priestley-Taylor model, those that make use of remote sensing of surface conditions, and those in which there is dynamic simulation of the evapotranspiration and water movement process in the soil-plant-atmosphere system. Although local adjustments to existing empirical models may be worthwhile, attention should be given to the physical and biological processes involved in order to decrease the possible errors in the evapotranspiration estimate.

No attempt will be made in this presentation to review all the evapotranspiration models and variants developed over the years. The recent paper by Monteith (1978) is a good reference on the development of evapotranspiration models since the Penman (1948) formula. It has been used considerably as a basis for this discussion and full credit should go to Professor Monteith for his contribution. Much of the discussion in this paper will be devoted to discussion of the Penman-Monteith combination model and to the Priestley-Taylor estimate of evapotranspiration from wet surfaces and to adaptations and applications of these approaches. An attempt will be made to summarize and compare the characteristics of the main models. Other recent reviews by Jensen (1974) and Doorenbos and Pruitt (1975) contain much useful information on empirical models for estimating evapotranspiration from various climatological variables. Webb (1975) has reviewed the different ways of estimating or measuring evapotranspiration from catchments.

Modeling evapotranspiration is, of course, not the same as measuring it, although sometimes both approaches are needed. Clearly, lysimeters and water-balance data provide a measurement of evapotranspiration, either directly or as a residual difference calcul ated from other measurements. The Bowen ratio-energy balance approach and the eddy-correlation technique also provide values of the latent heat flux above any evaporating surface, and these often have been used to provide reference values for evapotranspiration rates calculated by various models. No specific reference to the micrometeorological approaches to determination of evapotranspiration will be made here, although it is understood that certain models in regard to turbulent diffusion are included in these approaches.

In evapotranspiration modeling, one usually tries to make simplifying assumptions so that the evapotranspiration may be estimated over extended distances or periods of time, or both, so that some difficult measurements may be avoided, or so that climatological data or other easily obtainable data may be used. For example, in the original Penman model (1948), energy balance and turbulent diffusion equations were combined so that the difficult measurement of surface temperature could be avoided and only the four readily available variables of radiation, wind speed, air temperature and water vapor pressure were required. As we shall see later, attempts are now being made to measure surface temperature with radiation thermometers and to use this information in evapotranspiration estimates. The original Penman combination model actually provided an estimate of the evaporation from a free water surface and a factor then was used to get the potential evapotranspiration from a

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grass surface well supplied with water. The actual evapotranspiration under drying conditions was allowed for by defining a root constant so that as long as the soil moisture deficit was less than the root constant the potential evapotranspiration occurred. After that the rate of water loss decreased proportionately with an increasing soil-moisture deficit. The main equations in the Penman model were as follows:

$$E_o = \frac{\Delta Q_n + \gamma E}{\Delta + \gamma} \quad (1)$$

$$E_a = 0.35(e_d - e_a)(1 + \mu_2/100) \quad (2)$$

$$E_t = fE_o \quad (3)$$

$$E = (\Delta Rn + \gamma Ea)/(\Delta + \gamma) \quad (4)$$

where E_o is the evaporation from open water surface in mm/day

E_t is evapotranspiration from the well watered turf

Δ is the slope of the saturation vapor pressure curve at air temperature

y is the psychrometer constant

Q_n is the net radiation over open water

Rn is the net radiation over the vegetation

e_d, e_a and u are the saturation vapor pressure at the dew point temperature, and the saturation vapor pressure (millibars) at air temperature and the windspeed (miles/day) at the height of 2 m.

Penman later (Penman and Schofield 1951; Penman 1953) extended his approach to include diffusive resistance to water vapor movement from leaves, and Monteith (1963, 1965) extended this idea to a crop canopy by defining an aerodynamic resistance, r_a, in terms of the windspeed and aerodynamic roughness of the crop and derived a physiological resistance, r_c, from profiles of temperature, vapor pressure and wind above the crop canopy, This extended the Penman model for use over any vegetated surface. Monteith (1978) comments that the procedure for getting r_c was greatly criticized at the time it was proposed but cites recent experiments to indicate his model works well.

The Monteith model, or the Penman-Monteith model as referred to by Monteith (1978), can be written as follows:

$$LE = \frac{\Delta(Rn - G) + \rho C_p(e_d - e_a)/r_a}{\Delta + \gamma(1 + r_c/r_a)} \quad (5)$$

where LE is the latent heat flux

G is the soil heat flux

p and C_p are the density and specific heat of air

r_a is the aerodynamic resistance

r_c is the canopy resistance

and the other symbols were defined previously.

One experiment cited by Monteith (1978) to show that his model works was done by Black et al. (1970). They tested the model against a lysimeter measurement of the evapotranspiration from a snap bean crop.

Black et al. (1970) state that Monteith's model for evapotranspiration, E, from a crop may be written as

$$E = PE/\{1 + [\gamma/(\gamma+\Delta)](r_c/r_a)\} \quad (6)$$

where the potential evapotranspiration is

$$PE = [\Delta/(\Delta+\gamma)][(R_n - G) + (M/L)(\rho c_p/\Delta)(e_d - e_a)/r_a]. \quad (7)$$

and M is a constant to adjust units.

If the soil evaporation, E_s, is predicted separately the transpiration, E_t, can be written

$$E_t = (PE - E_s)/\{1 + [\gamma/(\gamma+\Delta)](r_c/r_a)\} \quad (8)$$

The value of the aerodynamic resistance is obtained by

$$r_a = \{\square + 1n[(z-d)/z_o\}^2/k^2u \quad (9)$$

where □ is the profile diabatic correction

d, z_o are zero plane displacement and roughness parameter

k = 0.4 is von Karman's constant

u is the windspeed at height z.

Data used by Black et al. (1970) include that from a period when the crop was exposed to two severe drying cycles. The authors draw attention to the separate estimation of the soil evaporation in their procedure and to their observation that the snap bean crop canopy used was loosely structured so that the resistance of the canopy air space was small in comparison with the stomatal diffusive resistance. That is, r_c was defined first by Monteith as a physiological resistance, but now it is more often termed crop resistance, canopy resistance, or surface resistance, and, according to Black et al. (1970), "r_c is a combination of soil, plant and canopy air space resistance, and is virtually impossible to measure directly."

Monteith (1965) stated that for a barley canopy with a leaf area index of L, r_c could be regarded as a combination of L leaf resistances in parallel. Thus, measuring with a diffusion porometer the stomatal resistance, r_s, of the leaves of a crop and dividing the average value, r_s by L, one obtains r_c. This is what was done by Black et al. (1970). Brun et al. (1973) tried different ways of getting r_s for a sorghum crop and found that averaging over all leaves of the canopy gave a satisfactory value of r_c. That is, when the relation $r_c = r_s/L$ was used in the Monteith model there was good agreement with the evapotranspiration values from a lysimeter. Again it should be noted that Brun et al. (1973) estimated the soil evaporation separately. It was assumed that it was equal to the net radiation below the crop canopy minus the soil heat flux. Black et al. (1970) considered that the evaporation from the soi l was considered to be either limited by the energy supply or limited by capillary flow to the soil surface.

Monteith (1978) states that actual evapotranspiration can be predicted if the appropriate value of r_c can be estimated from experience or, alternatively, he suggests one might use the ratio of actual to potential evapotranspiration determined by experiment for a particular combination of soil and crop and relate this to soil water content or potential. An example of the latter would be the study of Feddes and Zaradney (1978) who used a root extraction term that was dependent on the soil water potential. They also used the depth of the root zone, but the value of maximum possible evapotranspiration was provided by the combination equation. In principle, one would liketo beableto relate r_c to the water status of the soil, but there are complex relations involving the stomatai resistance, transpiration rate, leaf water potential, age of plant, etc. At least it is satisfying to know that using the combination model with *measured* stomatai resistances and leaf area index one can get reasonable values of the actual evapotranspiration (e.g., Brun et al. 1973), without the detailed gradient measurements needed, for example, in the Bowen ratio-energy balance approach.

Ahmed et al. (1976) were ableto relate canopy resistance to soil water status and developed a dynamic simulation model for the soil-water-atmosphere-plant system, in order to derive an optimum crop-irrigation strategy under simulated conditions of actual weather. Included in the model was a stomatai action subroutine which provided for the onset of stomatai closure at the appropriate leaf water potential, and the increase in leaf diffusion resistance at the appropriate rate with a further decrease in the leaf-water potential. A root water uptake model was used and with changing soil water content the leaf water potential was determined. This in turn affected the stomatai action, the transpiration, leaf area development, and photosynthesis. Of course in such a dynamic simulation there are several interactions under way simultaneously and the energy balance situation also would affect thetranspiration, leaf water potential and leaf resistance.

Another example of combining soil, plant, and climate information is that of Swift et al. (1975) who used the "Prosper" simulation model to determine the evapotranspiration and drainage for a forested and a clear-cut watershed over a 2-year period. The Prosper model applies a water balance to a vegetation stand and several soil layers. Evapotranspiration as in the Monteith approach is conceptualized as taking place from a single surface which is a combination of the ground and all canopy surfaces. The resistance of this surface to vapor diffusion is related to its water potential. Monteith's model is used to derive the vapor flow from the surface and this is equated to the liquid flow in the soil to the evaporating surface. The equation for liquid flow is derived by applying the law of conservation of mass and Darcy's law. In the model the energy balance equation is modified by inserting a function for the effective leaf area, because not all of a forest canopy is equally acting in the evapotranspiration process. The roots and the soil in each soil layer were interpreted as resistances in an electrical network and network analysis techniques were used to derive an equation for the flow of liquid water to the evapotranspiration surface as a function of surface water potential. There were no direct comparisons possible for the evapotranspiration from the forested watershed but experimental data from the Coweeta Hydrologic Laboratory showed that the annual totals of measured streamflow were within 1.5% of the simulated drainage. The model provided values of water potential for the evaporating surface and for the soil layers. Pecketal. (1977) used the same Prosper water budget model but included spatial variation of soil properties.

I think we will see further developments over the next few years in the dynamic simulation of the soil-plant-atmosphere system using equations for the various processes under way throughout the system and providing accurate and useful information on evapotranspiration and dry matter production.

Monteith (1978) notes that the minimum value of r_c for arable crops is about 40 s m^{-1} comparable with values of r_a. However, forests have much larger minimum values of r_c, and r_a is much smaller because of the greater aerodynamic roughness. Thus the evaporation rate of intercepted rainfall from forests exceeds that of normal transpiration while in crops the evaporation rate would be similar to the transpiration rate.

Thorn and Oliver (1977) commenting on the applicability of the Monteith method to the countryside note that the size and behavior of the effective value of the surface resistance for a regional area must depend on vegetation type, soil moisture deficit, amount of intercepted precipitation and time of year, but such difficulties need not be beyond practical solution. They also considered the variation of the aerodynamic resistance, r_a and found that Penman's simple empirical wind function (eq. 2) "is not only fairly realistic for a particular surface of quite small roughness but it can be employed almost with impunity over surfaces of relatively large roughness." From their analysis they suggest that for a typical rural lowland area of moderate aerodynamic roughness Penman's formula (eq. 4 above) be modified to

$$E = \{\Delta(Rn-G) + 2.5\gamma E_a\}/(\Delta + 2.4\gamma) \quad (10)$$

This equation was found to give better agreement with experimental observations of the overall evapotranspiration from catchment areas in Britain.

Other people have been interested in the estimation of evapotranspiration on a large scale using remote sensing. There is no doubt that the areal extent of cropped areas, and probably the kind of crop growing, the leaf area index, and the soil surface moisture content can all be obtained from remote sensing of the land surface. But, in order to obtain the evapotranspiration, one needs additional information. Idso et al. (1975) demonstrated that one could obtain evaporation from bare soil if one knew the daily solar radiation and the maximum and minimum air temperatures and the maximum and minimum soil surface temperatures. The evaporation rate from a moist soil of course is limited by the energy supply but, after drying, the soil water transmission affects the evaporation and the soil surface temperature rises relative to air temperature. Jackson et al. (1976) studied the transition between the energy-limiting and soil-limiting phases. They found the surface albedo was an excellent integrator of the surface dryness and they were able to partition, from the surface albedo, the fraction of the soil that was in the energy-limiting phase from that in the soil-limiting phase of evaporation. The inputs needed are a reasonable estimate of potential evaporation, albedo measurements for wet and dry soil before and during drying, and a value for the coefficient of the square root of time for soil-limiting evaporation rates (eq. 12). They used the Priestley and Taylor (1972) approximation for potential evaporation (discussed below)

$$PE = \alpha (Rn-G)\Delta/(\Delta+\gamma) \quad (11)$$

where a, they found, varied from 1.41 in summer to 2.41 in winter. For the dry soil they used the relation

$$E_s = Ct^{-1,2} \quad (12)$$

where C varied with soil type and with season as a result of temperature; t was the time in days after the soil became dry. They got excellent agreement between calculated results and lysimeter readings with this approach.

Heilman et al. (1977) used leaf area index values obtained from Landsat multispectral data to adjust the Priestley-Taylor evapotranspiration model for crop growth. The other input data were daily estimates of solar radiation (from which Rn was estimated), maximum and minimum temperature, and precipitation. Model outputs were potential evapotranspiration, transpiration, soil evaporation, actual evapotranspiration, drainage, and soil moisture in the 0 to 150 cm profile. Empirical factors were applied to the evapotranspiration model when the available soil moisture was less than 35%.

Stone and Horton (1974) and Blad and Rosenberg (1976) also have discussed experiments done with the objective of obtaining regional evapotranspiration using ET models that incorporate surface temperature data. Blad and Rosenberg (1976) used a mass transfer (Dalton) model for estimating evapotranspiration. That is, they measured windspeed and vapor pressure at 2 m and used a Bowen ratio-energy balance approach to provide the reference values needed to calibrate the wind function in the equation.

$$LE = f(u)(e_s - e_{200}) \qquad (13)$$

where e_s is the saturated vapor pressure at the temperature of the surface. They got reasonable agreement over alfalfa but point outthatthe mass transfer model, of course, will give increasingly worse results as moisture available to the crop becomes less and less and surface temperatures rise.

Blad and Rosenberg (1976) also used a "resistance model" in which they substitute for the sensible heat flux in the energy balance equation an expression that includes r_a, the aerodynamic resistance. That is, they write

$$LE = \rho C_p(T_s - T_a)/r_a + Rn - G \qquad (14)$$

$$\text{where } Rn = H + LE + G \qquad (15)$$

Thus one requires for this approach; (a) an appropriate value of r_a as a function of windspeed, surface roughness, and stability, (b) the difference in temperature between surface and air temperature, and (c) directly measured values of net radiation and soil heat flux. Monteith (1978) points out "that the main assumption of the 'model' — that the surface radiative temperature can be identified with the aerodynamic surface temperature — has still to be rigorously examined and tested for different canopy structures." Blad and Rosenberg (1976), however, found for daily periods that the agreement with the Bowen ratio-energy balance data was within 1 to 10% and for 15-minute readings during the daytime periods of 6 days the correlation coefficient was 0.844. Stone and Horton (1974) found that the resistance model gave results 22% greater than the Bowen ratio-energy balance comparison. Blad and Rosenberg (1976) believe this was because the Bowen ratio approach underestimates the evapotranspiration under advective conditions and that the "resistance model" probably provided the correct results. The reader is referred to papers by Rosenberg and his colleagues (e.g. Brakkeetal. 1978) for studies on the effect of advection on evapotranspiration.

An evapotranspiration model that has aroused a lot of interest in recent years is the simple formula proposed by Priestley and Taylor (1972). They said that for well-watered vegetation under nonadvective conditions the potential evapotranspiration (PE) may be represented by the expression

$$LPE = \alpha[\Delta/(\Delta+\gamma)](Rn - G) \qquad (15)$$

where a = constant = 1.26 was derived from several experiments in different climates. Jury and Tanner (1975) point out that the value of α = 1.26 may not be the best value for a given surface and locale, and they modified the expression to include a saturation deficit term to account for high local advection. That is, they proposed

$$\alpha' = 1.0 + (\alpha - 1)(e_s - e)/\overline{(e_s - e)} \qquad (16)$$

where $\overline{e_s - e}$ is a long-term mean saturation deficit for a period when advection is low.

They found that with an experimentally-determined α the Priestley-Taylor formula was as good as the Penman equation for determining daily average evapotranspiration from well-irrigated surfaces. They also found that a correction for advection can be made to improve estimates dn advective days. They suggest this approach to advection correction is deserving of further test.

Monteith (1978), however, notes that the experiments from which Priestley and Taylor obtained their data ranged from part of the Indian Ocean to a bean field in Wisconsin and that McNaughton (1976) pointed out that several sets of data used by Priestley and Taylor were inconsistent with their own criteria for saturated surfaces. Monteith (1978) also states that "the experimental evidence summarized by the ratio a = 1.26 cannot be consistent with the principles embodied in the Penman-Monteith formula unless there is very strong feedback between the canopy resistance of crops and the vapor pressure deficit in the air flowing over them." He continues, "Perhaps judgement should be reserved until we know more about the interaction of vegetation and the atmosphere. In the meantime, however, it is premature to reduce the Priestley-Taylor formula to a simple expression in which evaporation is estimated as a linear function of net radiant energy and mean air temperature (McIlroy 1977). It seems a retrograde step to introduce climatological formulae of this type, particularly when the limits of its applicability are so ill-defined in terms of the availability of water in the soil and the possible significance of large-scale advection of sensible heat in the atmosphere."

Another example of empirical adjustment of the empirically found α are the values determined by Davies and Allen (1973) as a function of surface soil moisture. Thus they proposed that α be considered as a variable, a, rather than a constant. Thus actual evapotranspiration could be expressed

$$LE = \alpha'[\Delta/(\Delta+\gamma)](Rn-G) \qquad (17)$$

They show a reasonably good relationship between a and surface soil moisture although they point out that their approach can only be recommended for bare soils and shallowly rooted plant covers. It seems to this author that it might be better to use the Monteith model (which will estimate actual evapotranspiration) and express r_c as a function of soil moisture or water potential, rather than to correct the Priestley-Taylor model (which was formulated to estimate the potential evapotranspiration). For a discussion of the relationship between the combination model and the Priestley-Taylor formulation, and to the variation of canopy (surface) resistance with moisture, the reader is referred to Davies (1972). Mukammal and Neumann (1977) were able to derive the effect of soil moisture deficits on evaporation from a lysimeter and evaporation pan by calculating the potential evapotranspiration by the Priestley-Taylor formula.

There are advantages, however, to a simple approach, and Selirio and Brown (1978), in a soil moisture-based simulation of forage yield, calculate the potential evapotranspiration by the Priestley-Taylor approach and then, using the basic ideas of the versatile soil moisture budget (Baier and Robertson 1966), they partition the actual water withdrawal from six soil zones. The ratio of actual to potential evapotranspiration is adjusted continuously as water is removed from a zone and is dependent on the evaporative demand (potential evapotranspiration). The simulated soil moisture values compare reasonably well with measured values obtained for six soil types used in the model validation.

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Derivation of Empirical Models to Predict Runoff on Small Agricultural Watersheds in the Semi-Arid Tropics

James G. Ryan and M. Pereira*

Summary

Multiple regression techniques are used to derive daily rainfall-runoff relationships under various soil, crop cover, land management, and agroclimatic conditions for two semi-arid tropical regions in south India. The fitted models were used to predict runoff on independent data sets, and they did so with a high degree of precision. Results suggest that the models can be used to estimate runoff with a minimum amount of data input. All that is required is information on soil types, whether the watershed is fallowed or cropped, area of the catchment, type of cultivation, and daily rainfall. The latter variable is by far the most important determinant of runoff. Alfisols had a much greater runoff-generating potential than Vertisols.

One of the elements in the design of improved soil- and water-management technologies for the semi-arid tropics (SAT) is the concept of harvesting excess runoff from small agricultural watersheds in water-storage reservoirs (or tanks) for subsequent use in supplementary irrigation of upland crops (Kampen et al. 1974; Krantz etal. 1978). In this way it is planned to be able to increase and stabilize agricultural production in the SAT.

Because of the uncertain nature of SAT rainfall patterns, and to evaluate the potential for water harvesting, it is necessary to determine the probability that viable quantities of runoff can be harvested and made available to upland crops at times when they can profitably respond to supplementary irrigation. Once rainfall-runoff and crop yield-irrigation relationships are known, these can be integrated into a simulation model, as shown in Figure 1. The economics of a water-harvesting and supplementary-irrigation technology can be evaluated from such a model and strategies/decision rules derived to enhance the economic performance of the system (Asfur 1972; von Oppen 1974; Ryan and von Oppen 1975; Smith 1978). These include evaluation of alternative irrigation timing and quantity rules; decisions as to whether to save harvested runoff for postrainy season double cropping or to use it during moisture-stress periods within the rainy season; derivation of optimal tank size/catchment ratios; and evaluation of seepage controls.

Another important application for a derived rainfall-runoff model is conversion of rainfall data into effective rainfall for use in the various water-balance models currently employed for assessing crop yield-soil moisture relationships. At present, most water-balance models, such as those developed by Fitzpatrick and Nix (1969) and Raman and Srinivasmurthy (1971), are unableto separate runoff and deep drainage from the soil profile.

The characteristics of the rainfall patterns in the SAT are quite different from those in the temperate regions of the world, where most of the hydrological runoff models have been developed. Kampen and Krantz (1977, p 21 indicate that rainfall intensities intheSAT are higher and interspersed with unpredictable droughts; the rainy season is short and its rainfall highly variable. For these reasons, and the fact that hydrologic research at ICRISAT Center has been conducted on watersheds of between 1 and 20

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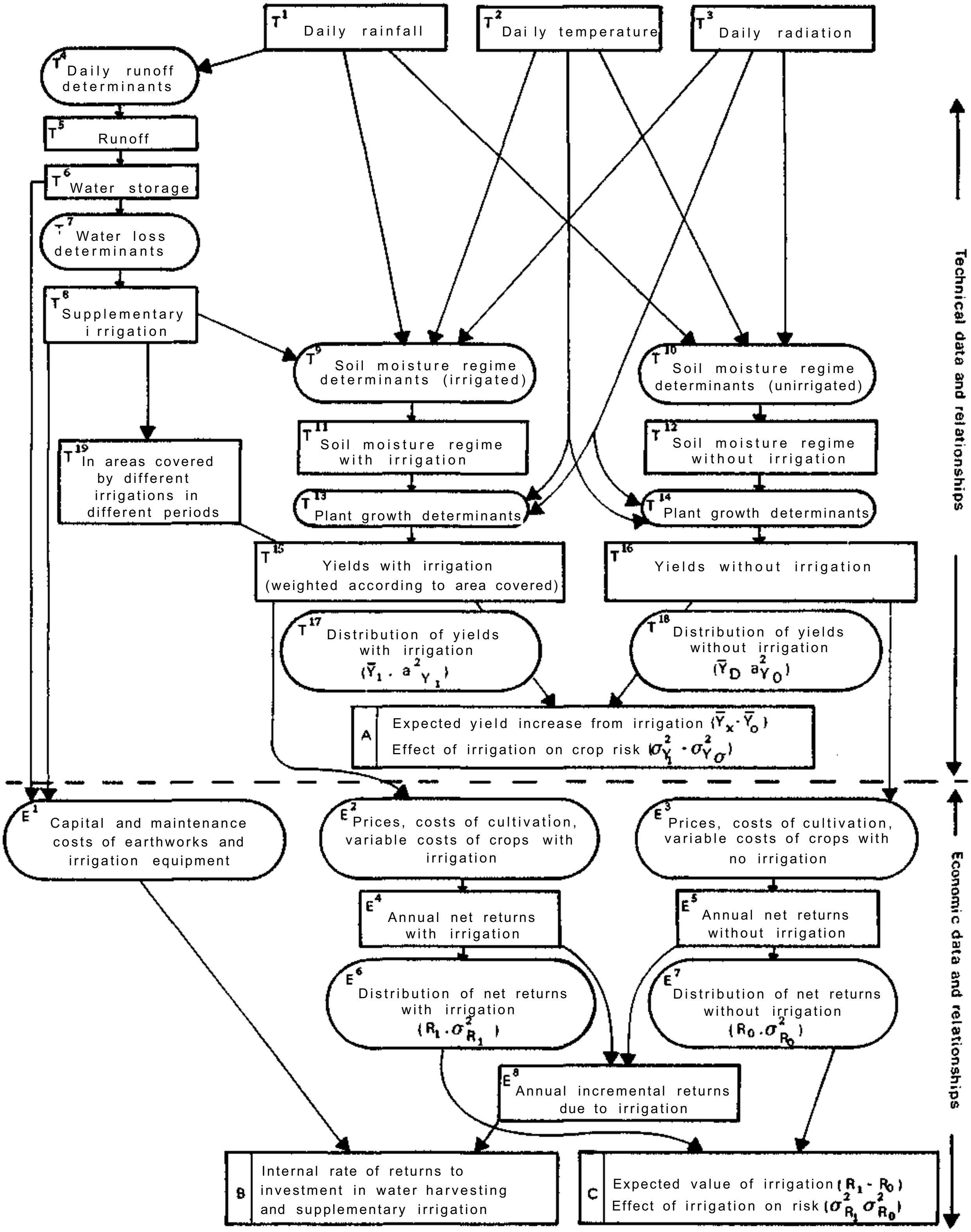

Figure 1. Simulation model of returns from water harvesting and supplementary irrigation.

ha, derivation of rainfall-runoff relationships using data generated on small SAT watersheds was deemed desirable.[1] Direct application of rainfall-runoff relationships derived in temperate zones with different soils and agroclimates was felt by ICRISAT's land-and water-management engineers to be inappropriate.[2] The extensive data from the hydrologic research on small agricultural watersheds conducted at ICRISAT Center, Hyderabad, Andhra Pradesh, from 1973-74 to 1977-78, and from small-plot research at the All India Coordinated Research Project for Dryland Agriculture (AICRPDA) Station, Shoiapur, Maharashtra, from 1951-52 to 1966-67, are used to derive the relationships.

Data Used for Analysis

Three different data sets were used in the analysis. The first consisted of the rainfall-runoff experiments conducted on deep and medium-deep Vertisol watersheds ranging in size from 0.33 to 11 hectares at ICRISAT Center near Hyderabad from 1973 to 1977. Usable daily rainfall-runoff data were available for 41 watershed-years in this data set, consisting of a total of 2531 daily rainfall events.

The second data set was from the same location, but was derived from rainfall-runoff experiments conducted on the small Aifisols watersheds. The data cover the 2 crop years 1975-76 and 1976-77, and consist of 11 watershed-years containing 839 daily rainfall observations. Sizes of the experimental watersheds on the Aifisols vary from 0.33 to 5 hectares.

The experiments at ICRISAT Center were designed to study, among other things, the influence of various factors on the hydrology of small watersheds. Major factors considered in the various treatments were soil type, method of cultivation, slope, type of bunding, vegetative cover, and watershed size.[3] Measuring the runoff potential of small watersheds under these various treatments was one of the primary objectives of the ICRISAT experiments reported in this paper.

The third set of data was derived from the plot experiments conducted from 1951 to 1967 at the Shoiapur Research Station of the All-India Coordinated Research Project for Dryland Agriculture in Maharashtra. The plots varied in size between 0.0017 and 0.0068 hectares and were designed primarily to measure soil losses on Vertisols under various land treatments. Data on both runoff and soil erosion were collected. A total of 14 114 daily rainfall events were recorded over all years and plot treatments. The treatments included a variety of cropping patterns generating different levels of vegetative cover, various rates of vegetative mulching, methods of cultivation, and types of bunding.

Hyderabad is located approximately 78°E longitude and Shoiapur at around 75°E. Both lie at 17°N latitude. The former has an average annual rainfall of 764 mm (1931-1960) while Shoiapur has 742 mm (undated). Both locations have a slightly bimodal rainfall pattern with a coefficient of variation of 26.1% for Hyderabad and 28.6 for Shoiapur (Virmani et al., 1978, p 8).

During the respective experimental periods, the ICRISAT Center site had an average rainy season rainfall of 803 mm, while at Shoiapur it was 637 mm (Table 1). Rainfall from June to October on the ICRISAT Vertisols generated around 14% runoff when averaged over all treatments (Table 2); on Aifisols, average runoff to the extent of 21% was generated. Runoff on the Shoiapur Vertisols (at around 10%) was much less than on either of the soil types at ICRISAT Center. Septem ber was the peak runoff month at all three sites.

The tendency for the Aifisols to generate more runoff than the Vertisols is further illustrated by the fact that 35% of the rainfall events occurring on these watersheds at ICRISAT Center generated runoff. Comparable figures for the Vertisol watersheds at ICRISAT Center and the Shoiapur Vertisol plots were 21 and 13%, respectively. The average number of rain-

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1. In the past, runoff measurements in the SAT have generally been made on plots less than 0.01 ha in size. Exceptions include the work of Kowal (1969) in Nigeria.
2. Personal communication from J. Kampen. A typical example of existing models is that of Hydrocomp International (1972).
3. For more details on these experiments, see the annual reports of the ICRISAT Farming Systems Program.

Table 1. Average monthly rainfall during experimental periods at ICRISAT Center and AICRPDA Sholapur.

	Rainfall[a]	
Month	ICRISAT Center (mm)	AICRPDA Sholapur (mm)
June	86	107
July	170	139
Aug	207	140
Sept	181	174
Oct	159	77
Total rainy season	803	637

a. At ICRISAT Center, the period of record was 1973-1977; at Sholapur it was 1951-1967.

fall events per year (around 70) was approximately the same at all three centers. On an average, only 25 mm of daily rainfall was required to generate runoff on the ICRISAT Center Alfisols, compared with 30 and 36 mm on the ICRISAT Center Vertisols and the Sholapur Vertisols, respectively.[4]

On these types of experiments, particularly those on the field-scale watersheds at ICRISAT Center, many variables influence the runoff process and interact together to generate the observed runoff. For example, the watershed having a treatment of 0.4% slope on a broad-bed-and-furrow system may have a higher proportion of long-duration crops than the watershed having broadbeds and furrows on a 0.6% slope. Hence, the differences in runoff between these two treatments will not be attributable solely to the differences in slope, but also to differences in vegetative cover. One must first adjust the runoff for the effects of the latter before attempting to measure the effects of the former. Multiple-regression techniques allow this to be done, and the balance of this paper describes the procedures and tests used to derive acceptable equations — which predict daily runoff with a high degree of precision — from the above experimental data.

4. A more detailed description of the data, methodology, and results of this study can be found in Ryan and Pereira (1978).

Methodology

The basic objective of this part of the research was to identify the functional forms and specifications of variables that wi ll generate the best predictions of runoff on an independent data set. Hydrological knowledge does not offer clear guidelines as to the form of the functional relationship between runoff and its determinants. It does suggest that, symbolically[5]

$$RO = f(X_i, W_j \quad \psi) \qquad (1)$$

where RO = runoff (mm/day)

X_i = vector of deterministic variables such as vegetative cover, type of cultivation, size of watersheds

W_j = vector of stochastic variables such as daily rainfall, rainfall intensity

ψ = random error

Many different functional forms describing the precise relationship in equation (1) were examined, and their relative efficiency in prediction measured. Linear, quadratic, semicubic, cubic, square root, logistic forms all with and without interaction terms between the deterministic and stochastic variables, were tested.

The range of variables tried in the various regression equations were as follows:

- Daily runoff (mm/day) (RO_t)
- Daily rainfall (mm/day) (RF,)
- Antecedent rainfall (mm/day)

$$(ARt = \sum_{i=1}^{5} RF_{t-i})$$

- Peak rainfall intensity (mm) during the peak 15-minute period of the daily rainfall event (PRI_t)
- Average rainfall intensity (mm) — measured as total daily rainfall per hour of rain (ARI_t)
- Vegetative cover — measured as an increasing index after sowing; reaches a maximum of 100 when crops reach their maximum leaf area index, and then declines to zero as leaf drop and harvest occur (VC_t)

5. See, for example, Amaracho (1967).

Table 2. Average monthly runoff on Vertisols and Alfisols at ICRISAT Center and on Vertisols at Sholapur during experimental periods.[a]

	ICRISAT Center				AICRPDA Sholapur	
	Vertisols		Alfisols		Vertisols	
Month	Runoff (mm)	Percent to total rainfall[6] (%)	Runoff (mm)	Percent to total rainfall[b] (%)	Runoff (mm)	Percent to total rainfall[b] (%)
June	5.1	5.9	0.4	0.5	13.4	12.5
July	6.9	4.1	30.6	14.3	9.3	6.7
Aug	25.7	12.5	60.9	27.7	6.8	4.9
Sept	43.5	24.0	69.0	29.2	26.0	14.9
Oct	31.3	19.7	21.3	21.2	7.1	9.2
Total	112.5	14.0	182.2	20.6	62.6	9.8

a. At ICRISAT Center, the Vertisol data relate to the 4 years 1973-1977; the Alfisols to the 2 years 1975-1977. The Sholapur Vertisol data relate to the 16-year period 1951-1967.

b. Total June-October rainfall only.

- Soil type — Alfisols or Vertisols
- Type of cultivation — traditional flat cultivation (FC)[6] or ridges and furrows on graded contours of various slopes
- Type of bunding —traditional field bunds (F), contour bunds (C), graded bunds (G), or no bunds.[7]
- Area of runoff plots or watersheds (ha) (A)
- Soil depth (cm) (D)
- Age of watershed — in years after initial land shaping (N)
- Mulching — quantity of mulch applied in (ton/ha) (M)

A number of criteria were employed to select from amongst the different models and variable specifications tried. Firstly, the rainfall-runoff data from each of the three sites were divided into two halves at random. The data file containing all the ODD-numbered observations was used to fit the multiple regression equation. The data file containing all the EVEN-numbered observations was then used to test the ability of the ODD regression to accurately predict runoff on the EVEN data set.

To test the efficiency with which different models and specifications predicted runoff on the EVEN file, Theil's (1965 pp 31-37) inequality coefficient (or U-statistic) was employed, along with sums of absolute annual linear deviations, and sums of squared deviations of individual observations. The U-statistic is defined in equation (2):

$$U = \left[1/n \sum_{i=1}^{n} (P_i - A_i)^2\right]^{1/2} \Big/ \left[\left(1/n \sum_{i=1}^{n} P_i^2\right)^{1/2} + \left(1/n \sum_{i=1}^{n} A_i^2\right)\right]^{1/2} \quad (2)$$

Where P_1 (i = 1, 2,——n) are the predicted values of n observations and A_1 are the corresponding actual values. The lower limit of U is 0, implying perfect prediction, and the upper limit is 1.

Theil decomposed the U-statistic into three components, U_m, U_s, and U_c. He termed these partial-inequality coefficients due to unequal central tendency (bias), unequal variation (variance), and imperfect covariation (covariance), respectively. This decomposition of U is important when U does not turn out to be zero, which is almost always the case. The most desirable values for U_m, U_s, and U_c when U = 0 are 0, 0,

6. Set up as dummy (0, 1) variables S_4, S_6, S_8, S_{10}, representing slopes of 0.4, 0.6, 0.8 and 1.0%, respectively.
7. Set up as dummy variables.

and 1, respectively. This configuration means that systematically repeated errors have been eliminated and that errors in prediction are unsystematic and cannot be improved by re-specifications of the model.[8]

Results for ICRISAT Center Vertisols

Data Truncation

The region of economic importance in the rainfall-runoff process for evaluation of water-harvesting and supplementary-irrigation potentials are those rainfall events generating substantial quantities of runoff. As about 80% of the rainfall events on the Vertisols at ICRISAT Center during the 4 years studied generated nil runoff, we examined the predictive accuracy of functions fitted using both the 0 plus non-0 runoff data (ZNZ) as well as only the non-0 (NZ). Each of these was randomized into an ODD and EVEN half to enable validation to be made.

We first tried a simple model involving daily rainfall as the only explanatory variable, as the simple correlation coefficient between daily runoff and daily rainfall was 0.83.[9] This is akin to the procedure used by Douglas (1974).

The form of the simple model was:

$$RO_t = \alpha+\beta(RF_t)2 \qquad (3)$$

The U-statistics and the error sum of squares for Equation (3), fitted using the truncated data set (ODD NZ) and predicting on the truncated data set (EVEN NZ), were much lower than the alternatives at 0.25.[10] The same was true when a more complete model such as shown in Equation (4) was fitted.[11]

8. Details of the calculation of the three components can be found in Ryan and Pereira (1978).
9. Using only NZ runoff observations.
10. That is equation 3 derived using either ODD NZ and predicted on EVEN Z N Z , or derived using ODD ZNZ and predicted on both EVEN Z N Z or EVEN NZ.
11. Addition of variables N and D to Equation 4, representing age of the watershed and average soil depth, respectively, had no effect on predictive accuracy. There coefficients also were not statistically significant.

$$\begin{aligned} RO_t = \alpha &+\beta_1(RF_t)^2 +\beta_2(VC_t) +\beta_3(A) \\ &+\beta_4(AR_t) +\beta_5(AR_t)^2 +\beta_6 S_4 \\ &+\beta_7 S_6 +\beta_8 S_8 +\beta_9 S_{10} \\ &+\beta_{10}(LC) +\beta_{11} F +\beta_{12} C. \end{aligned} \qquad (4)$$

The U-statistic in the case of Equation (4) fitted with ODD NZ data and predicted on the EVEN NZ set was lowest at 0.24. As a result of this, it was decided that subsequent model testing would be done only with the truncated NZ data sets.[12]

Choice of Explanatory Variables

The significant point, comparing the performance of Equations (3) and (4) in these Vertisol data from ICRISAT Center, is that the simple model performed almost as well as the complete model. The average absolute linear error of prediction of annual runoff with both models was around 16%. The average error, taking all 4 years together, was less than 3%.

When we tested the effect of deletion of the bund variables from Equation (4), all of which had nonsignificant regression coefficients at the 5% level, we found that the prediction results (U-statistics, linear errors, and sums of squared errors) were virtually identical. Hence these bund variables were deleted from further consideration.

Most of the coefficients on the ridge-and-furrow slope variables (S_4, S_6, S_8, and S10) in Equation (4) were not significant at the 5% level. However, as the absolute average annual error of prediction was about half when they were included in the model as when they were left out, it was decided to retain them. The U-statistics and error sums of squares of predictions were almost the same in the two cases, however.

We also tested for interaction effects on runoff between slopes of ridges and furrows and rainfall. To do this we compared Equation

12. This implies that when such models are subsequently used for simulation runoff from historical rainfall data, the rainfall data must first be truncated to remove observations less than the critical minimum level of daily rainfall required to generate NZ runoff. This will be treated further later.

(4) with one where each slope variable was interacted with $(RF_t)^2$ and added to Equation (4). The U-statistic for the interaction model was 0.32 compared with 0.24 for Equation (4). The error sum of squares was 55% higher for the interaction model, and the average annual linear error was 25% for the interaction, compared with 17% for Equation (4). Systematic errors (covariance, U_c) were 17% higher with the interaction model. We hence decided to utilize a noninteraction model for further analysis.

Rainfall intensity is postulated to be a prime determinant of runoff. Time-series data on rainfall intensity in the SAT are generally not available. Hence we endeavored to develop an empircal model that would predict runoff with sufficient accuracy in the absence of variable measuring rainfall intensity. The addition of either average (ARI_t) or peak rainfall-intensity (PRI_t) variablestothesimple model in Equation (3) had virtually no effect on U-statistics, linear errors, or on error sums of squares. The coefficient on ARI_t was negative but not statistically significant at the 5% level. That on PRI_t had the expected positive sign and was significant at the 5% level.

The addition of ARI_t to the complete model Equation (4) did not improve predictions, but the addition of PRI_t decreased the U-statistics marginally from 0.24 to 0.23, reduced the systematic error by 5 percentage points, and the absolute linear annual errors from 17 to 10%. Error sum of squares fell only marginally, by 3%. Hence, while inclusion of PRI_t does improve predictability on these Vertisols at ICRISAT Center, the absence of data on it is not likely to markedly affect the accuracy of simulated runoff predictions.

Examination of daily runoff predictions on EVEN NZ files using either Equation (3) or Equation (4) showed that one of the largest storms in the data set (10 Oct 1974) was consistently underpredicted. This 80-mm storm showed the highest peak intensity, 25 mm/15 minutes, over all 4 years and generated an average runoff of 65 mm. Even the models which included a PRI_t variable performed no better in terms of predicting this particular runoff event. A test was made to determine if regression equations fitted by deletion of this outlier storm gave improved predictions of the other runoff events. The regressions—Equations (3) and (4) without PRI_t included — fitted from the deleted ODD NZ files and used to predict on the nondeleted EVEN NZ files gave marginally reduced absolute errors, but increased the U-statistics from 0.24 to 0.25 and the systematic errors by 12 percentage points.

When Equations (3) and (4) were fitted (including PRI_t as a variable) using the deleted ODD NZ file, the coefficient on PRI, became nonsignificant. This suggests that, in all but the major storms, peak intensity does not play a major role in determining runoff. When these regressions were used to predict runoff in the nondeleted EVEN NZ file, there was virtually no improvement over the models fitted without PRI_t in them.

Throughout the analysis so far, we have mentioned only the quadratic formulation of the rainfall variable. It was compared with linear, cubic, semicubic, and logistic functions in both the simple and complete Equations (3) and (4). The quadratic always had the highest coefficient of multiple determination (adjusted for degrees of freedom) of around 0.83, generally the lowest absolute linear annual errors of prediction (17%) and U-statistics (around 0.24), and the lowest error sum of squares. Surprisingly, the linear form for rainfall, using a complete model Equation (4) formulation, had the lowest of all systematic errors at 0.1%. However, its U-statistic was 0.28 and error sums of squares were much higher than the quadratic — hence the latter was employed in all subsequent analysis. A variation of Equation (4), involving interactions between $(RF_t)^2$ and all other variables, gave slightly smaller linear prediction errors than Equation (4), but was rejected because of its higher U-statistic (0.30) and substantially higher error sum of squares and systematic error (33%).

Alternative specifications to $[\beta_4(AR_t) + \beta_5(AR_t)^2]$ used in Equation (4) for antecedent rainfall conditions were evaluated. These were $\beta_4(1/AR_t)$, $e^{(AR_t/100)}$, $[\beta_i(RF_t \sum_{i=1}^{7} RF_{t-i}) + \beta_i(RF_t \sum_{i=1}^{7} RF_{t-i})^2]$ and the precipitation index of Shaw (1963) $[\sum_{i=1}^{7} (RF_{t-i}/i) + RF_t/2]$. Of the four variants tried in place of the original in Equation (4), the third-namely

$$[\beta_i(RF_t \Sigma RF_{t-i}) + \beta_j(RF_t \sum_{i=1}^{7} RF_{t-i})^2]$$

was markedly superior. It was also far superior to the original formulation in Equation (4). It had a U-statistic of 0.18, an R^{-2} of 0.90, a systematic error of only 7%, and the lowest error sum of squares. It was also superior to formulations where the $(RF_t)^2$ variable was replaced with either linear, cubic, or semicubic terms along with the reformulated antecedent-rainfall specification. The selected model, which we will term ROVEHY (Runoff for Vertisols at Hyderabad), is presented in Table 3.

Applying Correction/Constraining Factors

The only antecedent rainfall interaction in ROVEHY with positive linear and squared coefficients was $(RF_t \cdot RF_{t-4})$. The interaction $(RF_t \cdot RF_{t-3})$ had a negative coefficient on the linear term and a positive coefficient on the squared term, implying a U-shaped effect on runoff. All other antecedent interactions had positive coefficients on the linear terms and negative on the squared terms, implying a n-shaped effect on runoff. As hydrologic theory suggests there can be no phase where increased antecedent rainfall leads to less runoff, we decided (for purposes of employing ROVEHY for simulation exercises) to specify that whenever the values of the antecedent rainfall interaction terms fall into that range we would constrain them either to zero [if their

Table 3. Selected model (ROVEHY) for runoff prediction (mm/day) on Vertisols at ICRISAT Center. Hyderabad.

Explanatory variables	Coefficients	Standard errors of coefficients
$(\text{Daily rainfall}_t)^2$ (mm^2/day)	0.00384366**	0.0002432
$(\text{Vegetative cover index})_t$	-0.0262092	0.01364
Area of catchment (ha)	-0.468341	0.3488
Ridge & furrow slope 0.4%[a]	-3.50010	1.9905
" " " 0.6%[a]	-3.51225	2.1924
" " " 0.8%[a]	2.49149	3.2118
" " " 1.0%[a]	-2.81718	3.0137
Flat cultivation*	0.50112	2.0287
(Daily rain_t) $(\text{Daily rain}_{t-1})$	0.0130421**	0.00218
(" " ") (" " $_{t-2}$)	0.00638437	0.00331
(" " ") (" " $_{t-3}$)	-0.0044155	0.00518
(" " ") (" " $_{t-4}$)	0.0003836	0.00825
(" " ") (" " $_{t-5}$)	0.0044443	0.00348
(" " ") (" " $_{t-6}$)	0.0137537*	0.00635
(" " ") (" " $_{t-7}$)	0.0070792**	0.00241
$[(\text{Daily rain}_t)\ (\text{Daily rain}_{t-1})]^2$	-0.177×10^{-5}**	0.0534×10^{-5}
[(" " ") (" " $_{t-2}$)]^2	-0.421×10^{-5}**	0.120×10^{-5}
[(" " ") (" " $_{t-3}$)]^2	0.1918×10^{-5}	0.377×10^{-5}
[(" " ") (" " $_{t-4}$)]^2	0.2829×10^{-5}	1.066×10^{-5}
[(" " ") (" " $_{t-5}$)]^2	-0.0554×10^{-5}	0.102×10^{-5}
[(" " ") (" " $_{t-6}$)]^2	-1.810×10^{-5}**	0.575×10^{-5}
[(" " ") (" " $_{t-7}$)]^2	-0.1389×10^{-5}*	0.0580×10^{-5}
$R^2 = 0.90$	n = 258	

* and** represent significance at the 5% and 1 % levels, respectively.

a. These are set up as dummy (0, 1) variables. When the effect of any one of them is being evaluated the variable takes the value 1 and all the other 4 variables take the value 0.

actual values were less than the value generating a minimum point (1151 in the case of $RF_t \cdot RF_{t-3}$)] or to their maximum values (3684, 758, 4010, 380, and 2549) in the case of $RF_t \cdot RF_{t-1}$ $RF_t \cdot RF_{t-2}$, $RF_t \cdot RF_{t-5}$. $RF_t \cdot RF_{t-6}$, and $RF_t \cdot RF_{t-7}$, respectively.

Having selected the constrained ROVEHY model in Table 3 for Ve'rtisols at ICRISAT Center, we generated actual, A, and predicted, P, runoff distributions from the ODD NZ file, using as class intervals the predicted runoff. We then estimated the average prediction error for each class *"k"* of predicted runoff as (A_k P_k). For runoff events of less than about 1 mm, the selected model led to underpredictions (i.e. A_k $P_k > 0$). For runoff events greater than about 1 mm, the constrained ROVEHY model tended to overpredict up to about 40 mm of runoff. Thereafter it again underpredicted. To determine if a second-round correction to the model, based on these residuals, would improve the model's predictive power on the other EVEN NZ file, we instituted a procedure which added the mean underprediction in each class interval where underprediction occurred on the ODD NZ file, and which subtracted the mean overprediction for the other class intervals. When the resulting prediction error distribution on the EVEN NZ file was compared with the original distribution, it was obvious that the correction factors substantially reduced the errors. This was borne out from the U-statistic, which fell from 0.20 on the constrained ROVEHY before correction, to 0.17 after correction. The error sum of squares fell by 10% and the average linear error from 25 to 10%.[13] However, at the same time, the systematic error increased by about 6 percentage points — from 1 to 7. In view of the other improvements from applying corrections, it was decided to proceed with the addition of these, in spite of the increased systematic error. The correction factors are listed in Table 4. The corrected/constrained ROVEHY model will be referred to a CROVEHY.

The CROVEHY model was used to predict runoff on a number of Vertisol watersheds at ICRISAT Center in 1977-78.[14] Four alternative data truncation rules were examined to determine which gave the best prediction. Runoff was predicted using CROVEHY for 1977-78 storms, with daily rainfall greater than the following:

1. the mean of the storms which generated zero runoff in the original experimental data (6.8 mm)
2. the above mean, plus one standard deviation (14.7 mm)
3. the above mean, plus two standard deviations (22.6 mm)
4. the above mean, plus three standard deviations (30.0 mm).

Generally, the best predictions for 1977-78, which was not a high rainfall year, occurred

Table 4. Correction factors to be applied to the constrained ROVEHY model to improve runoff predictions (CROVEHY).

Class intervals of predicted daily runoff from constrained ROVEHY (mm/day)	Correction factors (mm/day)
-8.00 to -4.01	+6.17
-4.00 to -2.01	+3.34
-2.00 to 0.00	+ 2.38
0.01 to 1.00	+ 0.35
1.01 to 2.00	-0.01
2.01 to 5.00	-0.63
5.01 to 10.00	-3.24
10.01 to 15.00	-9.57
15.01 to 20.00	-8.42
20.01 to 30.00	-7.97
30.01 to 40.00	-1.65
40.01 to 50.00	-6.14
50.01 to 200.00	0

13. When the same correction procedure was performed on the unconstrained ROVEHY model, the U-statistic fell to 0.14. The error sum of squares was 30% less than the corrected constrained ROVEHY model. However, the systematic error of the unconstrained ROVEHY after correction was much higher at 25% (compared to 7% for the constrained ROVEHY). Due to the latter, plus the theoretical argument cited earlier, it was decided to utilize the constrained ROVEHY for further analysis.

14. Recall that the 1977-78 rainfall-runoff data were not used in the estimation of CROVEHY.

when the fourth data truncation procedure was used. Hence we suggest applying CROVEHY only for daily-rainfalls in excess of 30 mm on ridges and furrows and 22 mm on flat cultivation. Runoff of zero is predicted for storms of this size or less on Vertisols at ICRISAT Center.

One of the striking points in the whole analysis for these Vertisols at ICRISAT Center was the consistency in the size and sign of the Coefficient on $(RF_t)^2$, no matter what other variables or specifications were used in the equation. It generally took a value around + 0.0045. In the absence of data on other variables, this might be used as a first approximation to the runoff coefficient on soils similar to the Vertisols at ICRISAT Center and where the rainfall pattern is also similar.

Results for Sholapur Vertisols

The procedures used to derive a prediction equation from the more extensive runoff data available for the Sholapur Vertisols were virtually identical to those used on the Vertisols at ICRISAT Center. Except for one additional variable, representing mulching treatments given at Sholapur but not at ICRISAT Center, the variables and the final selected specification of the runoff model was the same for the two locations. Of course, the coefficients on the variables were different. The final equation (ROVESH), chosen to represent runoff on the Vertisols of Sholapur, is presented in Table 5.

In the application of ROVESH, constraints on the antecedent rainfall interaction terms should be applied, as was the case for CROVEHY. With ROVESH, if the values of $RF_t \bullet RF_{t-3}$ and $RF_t \bullet RF_{t-4}$, are less than 1204 and 713, respectively, they are taken as 0 — because these are minima. If their values exceed 1204 and 713, the actuals are used. If the values of $RF_t \bullet RF_{t-1}$, $RF_t \bullet RFt_{t-2}$, and $RF_t \bullet RF_{t-6}$ exceed 4810, 10 156,

Table 5. Selected model (ROVESH) for runoff prediction (mm/day) on Sholapur Vertisols.

Explanatory variables	Coefficients	Standard errors of coefficients
(Daily rainfall$_t$)^2 (mm^2/day)	0.0019854**	0.0001
Vegetative Cover index),	-0.0369555**	0.00796
Area of plot (ha)	-1001.55**	184.74
Flat cultivation[8]	8.73175**	0.969
Mulching (tonnes/ha)	-0.895754**	0.168
(Daily rain,) (Daily rain$_{t-1}$)	0.000976184	0.000715
(" " ") (" " $_{t-2}$)	0.00229525*	0.00111
(" " ") (" " $_{t-3}$)	-0.00137913	0.000958
(" " ") (" " $_{t-4}$)	-0.00859539**	0.00284
(" " ") (" " $_{t-5}$)	0.00224592	0.001209
[(" " ") (" " $_{t-6}$)]^2	0.00141985	0.001072
[(" " ") (" " $_{t-7}$)]^2	0.00430554*	0.001869
[(Daily rain$_t$) (Daily rain$_{t-1}$)]^2	-0.0101458 x 10^{-5}	0.0154 x 10^{-5}
[(" " ") (" " $_{t-2}$)]^2	-0.0112926 x 10^{-5}	0.0375 x 10^{-5}
[(" " ") (" " $_{t-3}$)]^2	0.057279 x 10^{-5}**	0.0155 x 10^{-5}
[(" " ") (" " $_{t-4}$)]^2	0.602437 x 10^{-5}*	0.2615 x 10^{-5}
[(" " ") (" " $_{t-5}$)]^2	0.0333569 x 10^{-5}	0.0243 x 10^{-5}
[(" " ") (" " $_{t-2}$)]^2	-0.0752188 x 10^{-5}**	0.01885 x 10^{-5}
[(" " ") (" " $_{t-2}$)]^2	0.0826648 x 10^{-5}	0.0772 x 10^{-5}
R^2 = 0.67	n = 868	

* and ** represent significance at the 5% and 1 % levels, respectively.

a. This dummy variable takes the value of 1 when there is flat cultivation and of 0 if there are ridges and furrows.

and 937, respectively, then these maxima are employed. If they are less than these maxima, actual values are employed. There are no restrictions on $RF_t \cdot RF_{t-5}$ and $RF_t \cdot RF_{t-7}$, as these are monotonically increasing functions.

Application of residual correction factors to the Constrained ROVESH model resulted in a slight increase (0.29 to 0.30) in the U-statistic, a 1% reduction in error sum of squares, and slightly improved linear predictions. Hence the constrained/corrected ROVESH model was selected as best representing the runoff process in the Sholapur Vertisols. Constrained ROVESH should be used for daily runoff equal to or greater than 36 mm. For daily runoff less than this, runoff on Sholapur Vertisols is estimated to be 0.

We used the Constrained ROVESH model in Table 5 to predict runoff on the ICRISAT Center Vertisols, employing the actual rainfall-runoff data for the 4 years of experiments there. We also did the reverse — namely, used Constrained ROVEHY on the Sholapur Vertisol actual rainfall-runoff data. There are many difficulties in doing this. First of all, the size of the runoff plots were markedly smaller in Sholapur. Hence one sees a coefficient on area of -1001.55 in CROVESH and only -0.468341 in CROVEHY. It is obvious that these area coefficients are applicable only over the range of data used to derive them. Hence for cross-predictions, we used the mean of the plot areas in Sholapur when applying Constrained ROVESH to ICRISAT Center, and *vice versa* for constrained ROVEHY.

When predicting for Sholapur with CROVEHY, it was also assumed the effect of mulch was similar to full vegetative cover, and that the average slope of ridges and furrows was 1%. When predicting for ICRISAT Center with CROVESH, mulch was assumed to be zero, and the comparison was made using flat cultivation only, as there was no variable for slopes of ridges and furrows in Constrained ROVESH.

Results of the cross-predictions showed that, after first-round corrections, CROVEHY used on the Sholapur data had a U-statistic of 0.38, a systematic error of 21%, and an error sum of squares of 82 000. This compared with values of 0.29, 21%, and 51 000 for the CROVESH model fitted on the same Sholapur data. There generally were large underpredictions for small runoff events and large overpredictions for large runoff events. It is clear from this that the Constrained ROVEHY model derived from ICRISAT Center data does not predict in Sholapur nearly as well as the Constrained ROVESH model derived using Sholapur data.

The Constrained ROVESH model applied to the ICRISAT Vertisols data generally performed better than the reverse predictions described above. It gave a U-statistic of 0.23, 14% systematic error, and an error sums of squares of 14 000 mm^2. This compared to a U-statistic of 0.17 for the CROVEHY model on the ICRISAT Vertisol data, a systematic error of 7%, and an error sum of squares of 8000 mm^2. Constrained ROVESH underpredicted low runoff events and overpredicted heavy runoff events at ICRISAT Center.

Results for ICRISAT Center Alfisols

Similar testing procedures were used to derive a runoff prediction model for the Alfisols at ICRISAT Center. We found that inclusion of any formulation of the antecedent rainfall or vegetative cover variables made the predictions much worse. Their coefficients also generally had unexpected signs and were not significant, and hence AR and VC were dropped from the model.

The peak rainfall intensity variable turned out to be a highly significant explanatory variable in the finally selected runoff equation, which was of the form:

$$RO_t = \beta_1 (RF_t)^2 + \beta_2 A + \beta_3 (FC) + \beta_4 (S_4) + \beta_5 (S_6) + \beta_6 (RF_t)^2 (S_4) + \beta_7 (RF_t)^2 (S_6) + \beta_8 (PRI_t) \quad (5)$$

The effect of inclusion of PRI in Equation (5) on predictions on the EVEN NZ file, however, was not dramatic. When it was included, the U-statistic fell from 0.21 to 0.18, the systematic error from 19 to 5%, and the error sums of squares by 30%. However, the average absolute linear errors of prediction increased slightly — from 14 to 15%.

As mentioned previously, for purposes of simulation, it is not possible to utilize historical data relating to PRI_t, as it is not available. To adjust for this, we fitted a regression equation with PRI_t (mm/15 minutes) as the regressand and RF_t (mm/day) as the regressor, using 4 years of data from ICRISAT Center. The following equation resulted:

$$PRI_t = 0.214265^{**}(RF_t) \qquad R^2 = 0.59 \qquad (6)$$
$$(0.014284)$$

We refitted the model in Equation (5) with the estimated peak rainfall intensity ($EPRI_t$) variable in Equation (6) used in place of actual PRI_f. The resulting ROALHY for runoff prediction on Alfisols at ICRISAT Center Hyderabad is presented in Table 6. The ROALHY model had a U-statistic of 0.19, compared to 0.18 for the model with PRI, included, an error sums of squares of 7100 compared to 6300, a systematic error of 8% compared to 5%, and an average annual linear error of prediction of 13% compared to 15% with the PRI, model. The ROALHY formulation including EPRIt was also far superior to the ROALHY model with EPRIt deleted.

Application of first-round correction factors to ROALHY did not bring improvements in predictions and hence the model in Table 6 can be used directly for purposes of prediction when daily rainfall exceeds 17 mm on flat-cultivated areas and 25 mm on areas in ridges and furrows. For rainfalls less than these amounts, runoff is estimated to be zero.

Conclusion

The results suggest that the empirical models derived here for determining runoff on Vertisols and Alfisols in two areas of India will enable predictions to be made with quite a high degree of accuracy. This accuracy will be greater the more one moves away from daily predictions and sums them into weekly, monthly, and annual totals. The latter can be predicted on average with less than 10% error in somecases.

The type of specification which generated the most-accurate predictions was essentially the same on the Vertisols of ICRISAT Center, Hyderabad, and those at the AICRPDA Station, Sholapur. However, coefficient values were substantially different in the two cases and cross-predictions were not all that good when compared with predictions with models developed with data from the same location. The cross-predictions were best when the constrained ROVESH model for Sholapur Vertisols was used to predict runoff on the Vertisols at ICRISAT Center. The major reason for the problems with cross-prediction may be due to the vastly different catchment sizes used on thetwo sites, rather than the existence of a basically different runoff process. Further work on this aspect is being planned.

Table 6. Selected model (ROALHY) for runoff prediction (mm/day) on Alfisols at ICRISAT Center, Hyderabad.

Explanatory variables	Coefficients	Standard errors of coefficients
(Daily $rainfall_t)^2$ (mm^2/day)	0.00252509**	0.00071
Area of Catchment (ha)	-0.139692	0.7150
Flat cultivation[8]	-0.502341	1.2323
Slope 0.4% ridges and furrows[b]	0.441861	1.1831
Slope 0.6% ridges and furrows[c]	0.179038	1.8473
(Daily $rainfall_t)^2$ ↑ (Slope 0.4% ridges and furrows)[b]	0.000033081	0.00047
(Daily $rainfall_t)^2$ ↑ (Slope 0.6% ridges and furrows)[c]	0.00307569**	0.00046
Estimated peak rainfall intensity	0.441613	0.2712
$\bar{R}^2$ = 0.91		n = 153

** represents significance at the 1% level

a. If the area is flat cultivated, this variable takes a value of 1 and both ridge-and-furrow variables and their interactions take the value 0. If the area consists of ridges and furrows, then the flat cultivation variable takes the value 0.

b. If 0.4% ridges and furrows are being evaluated, this variable takes the value 1 in both the Interaction term and the Intercept term, and 0 otherwise.

c. If 0.6% ridges and furrows are being evaluated, this variable takes the value 1 in both the interaction term and the Intercept term, and 0 otherwise.

The consistency in the value of the coefficient on $(RF_t)^2$ at around + 0.0045 in the many formulations tried on the Vertisols at ICRISAT Center was a significant feature of the results. This suggests that, in the absence of information on other variables influencing runoff, this value might be used as a first approximation of daily runoff in areas with similar rainfall patterns and soil types.

Finally, it is recognized that the empirical models derived in this study are in fact the "reduced forms" of hydrological processes consisting of many "structural relationships" that are not captured in these empirical models. Understanding the processes involved is an important aspect on which a better understanding is required, particularly on small agricultural watersheds in the SAT. The "reduced form" approach used here was forthe explicit purpose of enabling runoff to be predicted accurately, rather than to be explained, in order to assess the economic potential for a water-harvesting and supplementary-irrigation technology. The derived equations will now be employed in the simulation exercises outlined earlier in this paper.

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Session 3

Crop-Environment Interactions

Chairman: J. S. Russell
Co-chairman: C. Charreau

Rapporteur: N. Seetharama

Summary and Recommendations

This session was the third in a logical sequence in this workshop. The first session was largely concerned with climate itself, methodologies of data collection, and aspects of geographic distribution of various climatic parameters. The second session was concerned mainly with water balance and water loss and with the climate-soil interface. This session involved an additional dimension, that of the plant itself and of plant variation and reaction to stress.

There were five papers in this session. Two papers, by Dr. Bidinger and Dr. Sivakumar, emphasized the great strides that have been made in the last decade in the characterization of plant response to water stress. Dr. Bidinger discussed the effects of water stress on cell division and growth and the importance of stomatal conductance as a plant mechanism for alleviating water stress. Dr. Sivakumar discussed the range of techniques that are now available for quantifying water stress. These include the plant parameters of stomatal resistance, leaf water potential, leaf area, and leaf temperature. The other three speakers (Dr. Shaw, Dr. Venkataraman, and Dr. Stewart) gave specific examples relating climatic parameters to plant behavior and yield. Dr. Shaw made the point that source-sink relationships differ between species and that more attention needs to be paid to identifying these. He also stressed the local nature of empirical models. Dr. Venkataraman indicated the need for standardizing methodology for estimating assured rainfall amounts for different areas and for the testing and validation of models. Dr. Stewart gave a number of examples of functional relationships between climatic parameters (total sunshine hours, seasonal evaporation) and plant yields, which he suggested were transferable. He also emphasized the sequential aspect of limiting factors and the need to identify the most important limiting factors in any environment. In the SAT, water is the most important factor to be considered. However, potential yield is determined by a sequence of factors beginning with seasonal energy availability, plant population, soil fertility, etc., and waier deficits operate on this potential.

Recommendations

The papers and discussion they generated provide a basis for consideration of future research at ICRISAT.

A number of recommendations were presented as follows:

1. The recently developed technology for measuring plant water stress has greatly increased our potential to understand both plant mechanisms and the ability of some plants to adapt to necessary stress. Research should be continued and extended into characterizing plant species and cultivars grown in the SAT. It is possible that specific drought-tolerant plants could be used in breeding programs.
2. Plant modeling is a valuable tool for initially forcing consideration of plant mechanisms and ultimately of predicting plant behavior. The development of climate-soil-plant models is an evolutionary process beginning with simple models. The template for this development is a knowledge of plant phenology as affected by daylength and temperature. There are important differences between cultivars of the same species and many of these are not understood enough to be modeled. The modifying effects of water stress and nutrition also need to be evaluated, even though the magnitude of these effects is often minor in comparison with daylength and temperature. Fortunately, in comparison with temperate areas, vernalization effects are rarely important in crops grown in the SAT.
3. Consideration should be given to the use of serial planting techniques for the delineation of phenology of the main crops to be studied at ICRISAT. Hyderabad is probably not suited to this because of its small range of daylengths. What is required is a site at as high a latitude as possible at which crops such as sorghum

can be grown year round (under irrigation). A wide range of cultivars could be handled (possibly 20 to 30 of each crop) and replication over 2 years should enable obtaining the basic data that is required for modeling plant growth.

4. There is a dilemma in any modeling carried out by ICRISAT. On the one hand it is important that general models be developed that can be applied in the SAT generally. This suggests a sophisticated approach using process models, where possible. On the other hand, in areas of the SAT only rudimentary agrometeorological data are available; this means that simple models using minimal inputs are required. Nevertheless with ingenuity and skill such models are being developed; the Arkin, Vanderlipp, and Ritchie sorghum model is an example of this approach.

5. More attention could be given to aspects of root growth. The setup at ICRISAT is suitable for the large human inputs that are necessary in these studies. Research on rates of root growth as affected by soil root patterns, on partition between roots and tops under stress conditions, and differences between cultivars in ability to extract waterfrom the soil profile need to be studied in greater detail.

6. More advantage could be taken of the unique "rainout" *rabi* season conditions at Hyderabad and other areas of the SAT such as in the major river basins in Africa for the study of crop water stress under a range of different water regimes. Some bias is introduced in such studies, e.g., by different daylengths and humidities from which the crops are grown in practice, but with adequately disigned experiments, fundamental knowledge of plant behavior could be obtained with such studies.

7. Although emphasis on water stress needs to be continued, the possible effects of other climatic factors should not be overlooked. These includethe effect of cool temperatures, large variations between day and night temperatures and excess water periods as limitations to plant growth in the SAT. The possible existence of useful varietal differences to such effects needs to be evaluated further.

8. New and simpler techniques (e.g. leaf temperature) need to be developed for screening genotypes for drought resistance.

9 Recommendations should be made by ICRISAT for the use of apparatus for measuring plant stress in difficult conditions in developing countries.

10. There is such a large range of models available for the estimation of evaporation that ICRISAT should consider producing an authoritative publication classifying these models and indicating their usefulness in relation to the data available.

11. ICRISAT should consider contributing to the training courses in agroclimatology, particularly for people in Africa. Interdisciplinary cooperation also needs to be given the fullest support.

Water-Stress Effects on Crop-Environment Interactions

F. R. Bidinger*

Summary

The effects of stress on crops considered in this paper are: (a) reduction in the rate of cell division and expansion and (b) stomatal closure. These are only two of a whole range of plant processes affected by moisture stress. They were chosen for examination for two reasons: they are relatively better understood than many of the other effects of stress (particularly those at a biochemical level), and they play a major role in the relationship between the crop and its environment.

Effects of reduced cell division or expansion on leaf area expansion are most important following, rather than during, the period of stress. A reduced leaf area means the interception of a lesser percentage of the incident radiation, which will have a direct effect on crop growth rates if the latter are radiation limited. Concomitantly, a greater percentage of the incident radiation falling on the soil surface will increase the evaporative component of crop ET at the expense of the transpiration component. Effects of reduced cell expansion on root growth, in contrast, are most important during the stress period itself, as the maintenance of even a limited supply of water to the crop depends upon continued root extension into deeper zones of the soil profile where some moisture may be available.

A reduction in stomatal conductance affects a number of crop/environment interactions as the stomata are the control point for both vapor and energy exchange between crop and environment. A reduction in rate of water loss from the crop is of immediate advantage in protecting the crop from direct desiccation effects. The conservation of soil moisture by stomatal closure may also be of benefit under certain circumstances.

Stomatal closure, however, also changes the normal leaf energy balance and places an extra load on the sensible heat component. Resulting increases in leaf temperature increase the water vapor concentration gradient between leaf and air and in extreme cases expose the leaf to possible direct heat injury. In addition, the protection afforded by stomatal closure is at the cost of reduced carbon assimilation and (depending upon the relative magnitude of internal, stomatal, and crop boundary-layer resistances) possibly at the cost of a decrease in crop water-use efficiency.

Water deficits (negative water potentials) are a necessary and constant condition of terrestrial plant life. Solar energy falling on crops and natural plant communities is manyfold that required for photosynthesis. If converted to sensible heat, this excess energy would raise the earth's surface temperature well beyond levels compatible with most forms of life. More than 70% of this energy, however, is used in changing the water present in soil surface layers and (particularly) in plant communities from liquid to vapor. Excess solar energy is thus disposed of as the water vapor diffuses from the immediate surface layer of the earth into the atmosphere.

Water lost from plants in dissipating solar energy is evaporated mainly from the walls of cells lining the inner stomatal cavities in plant leaves. This leads to a decrease in the chemical potential (water potential) of the water remaining in these cell walls. Because water in plant cellsforms a continuous system throughout the plant, this negative potential is transmitted to and along the water in the xylem system, from leaf to root. The process establishes a potential

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gradient between the root and the soil, and causes water to move from the rhizosphere into the root. This potential gradient between leaf and soil (and the resulting water movement from soil to leaf) is maintained by continued evaporation frorn leaves.

The degree of water deficit in the leaf is dependent mainly on the rate of evaporation from the leaf (i.e., mainly on solar energy) and on the chemical potential of water in the soil (i.e., on the degree to which the water potential of the root must be decreased to establish a gradient from soil to root). Modest water deficits are the normal state for crops and natural plant communities, and are not damaging to plant function. As available soil water is depleted, and soil-water potentials become more and more negative, plant-water potentials also become more negative, and plant-water deficit becomes plant-water stress. There is no clear threshold at which water deficit becomes water stress. The only way of assessing this is by observing plant function. When plant function is impaired, the plant may be considered to be under stress.

The most sensitive field method currently available for estimating when a plant is under stress is the measurement of stomatal conductance. Stomata are very sensitive to small changes in leaf-water potential (Turner 1974) and transpiration rate (Hall and Hoffman 1976) as the leaf-water potential approaches a critical threshold level. In addition to their sensitivity, the stomata are useful indicators of stress because changes in stomatal conductance have major effects on the crop and on its relationships with its environment; these will be considered in detail in this paper.

Nearly all crop plants are subject to water stress some time during their life cycle. It may be for only a few hours, on occasional days, when high rates of irradiance and/or high rates of evaporation cause a temporary decrease in stomatal conductance, even in "well watered" crops. Alternatively, stress may be due to declining soil-moisture availability, such that the soil is unable to furnish water at a rate sufficient to maintain plant-water potential at a nonstress level for more than a few hours in the morning of each day.

The magnitude of the effects of stress on short-term plant function and longer-term crop growth and yield are dependent upon the intensity, duration, and time of occurrence of the stress. The effects of stress are predictable only in a general way and only for certain individual plant developmental or physiological processes. Although much has been learned aboutthe nature and effects of stress in the last decade, much more remains to be learned.

This paper is limited to a discussion of the consequences of two important plant responses to stress — cessation of cell division and expansion, and stomatal closure — on the crop and on the interactions between the crop and its environment. For a more comprehensive discussion of the effects of stress on plants, crops, and natural communities, the reader is referred to review articles by Hsaio (1973), Begg and Turner (1976), and Fischer and Turner (1978).

Stress Effects on Cell Division and Cell Expansion

The effects of moisture stress on rates of cell expansion and cell division have been known for a long time (Stocker 1960), partly (at least) because tools to measure these effects have been available for a long time. There has been some discussion in recent review articles as to which process is the more sensitive to stress (Hsaio 1973; Begg and Turner 1976). The general conclusion is that cell expansion is the more sensitive process, at least in cases of mild to moderate stress, but this has been questioned (McCree and Davis 1974).

Reduction in the rates of cell division and expansion has generally similar effects on crop growth — a reduction in the size of the tissue or organ undergoing rapid growth during thetime the stress occurs. Reductions in rates of cell division at certain critical times may have particularly severe effects on crop yields — that is, at floral initiation (when potential flower numbers are determined) or at macro- and microsporogenesis (when competent flower numbers are determined) (Slatyer 1969).

From the standpoint of crop/environment interactions, however, two consequences of reduced cell expansion or division are of major importance: a reduction in crop leaf-area index, and a reduction in the rate and amount of root growth. Each will be considered in some detail.

Reduction in Leaf-Area Index

Although leaf expansion under field conditions is not as sensitive to water deficits as thought from controlled-environment experiments (Begg and Turner 1976), reductions in leaf area are one of the most common and most visible effects of stress. Reduction in leaf area is also a permanent effect: a small leaf remains a small leaf. Thus the effects of even a short-duration stress may persist for a long period.

Radiation interception by crops is directly (although somewhat curvilinearly) related to leaf-area index, up to the point of "full ground cover," or about 95% light interception. The particular leaf-area index corresponding to this point varies with the nature of the crop canopy (i.e., vertical or horizontal leaves) and with the geometry and population at which the crop is planted. A survey of the literature (Monteith 1969) reported values of LAI at full cover as low as 2.9 for cotton to as high as 10 for ryegrass, with mostcropsfalling intherangeof 3.5to5.0.

Thus the effects of reduction in rate of leaf expansion on radiation interception will depend on the crop, the row spacing, and the stage of growth or the LAI at which the reduction occurs. If the crop is at a stage in which growth rate is limited by radiation interception, any reduction in leaf-area index will result in a reduction in crop assimilation and in crop-growth rate. This may be less important during the period of moisture stress (as crop assimilation may be affected by stomatal conductance as well) than during the poststress period, when crop growth will be mainly a function of radiation received.

A reduction in energy intercepted by the crop means an equivalent increase in the energy falling on the soil surface. When thesoil surface is dry, there will be little effect on soil evaporation. Increased heating of the soil surface may result in some transfer of sensible heat to the crop, increasing its energy load. This effect has been shown to occur for wide-row (1 m) sorghum crops in the Great Plains of the USA. Up to 64% of the net radiation falling on the dry soil surface was used in transpiration from the crop (Hanks et al. 1971).

However, during periods when the soil surface is wet, a greater fraction of the radiation falling on the soil surface results in an increase in the evaporation component of crop ET, at the expense of the transpiration component (Ritchie and Burnett 1971). In an intermittent-rainfall environment the evaporation component of ET can be substantial, particularly early in the season when crop leaf areas are small. Estimates of this at ICRISAT Center the last several years show that approximately 25% of total seasonal crop ET represents evaporation from the soil surface (M. B. Russell, personal communication). From the crop standpoint this is wasted water, particularly in an environment in which water deficits are a major limitation to crop production. Because of this, a number of investigators have suggested narrower row spacings and higher plant populations to maximize the ratio of transpiration to evaporation (Chin Choy and Kanemasu 1974).

Effects on Root Growth

We know much less about the effects of reduced cell division and reduced expansion on root growth, despite the critical importance of continued root growth during periods of stress. Root growth would appear to be less affected than top growth, as root/shoot ratios have been reported to increase in a variety of crops during stress periods (cf. reviews by Slatyer 1969; Hsaio and Acevedo 1974).

There are two possible reasons for this — either root meristems are not subjected to the same degree of water stress as are shoot meristems, or root meristems have a differential ability to continue cell division/expansion under stress conditions. Osmotic adjustment has been shown to occur in the roots of at least one species (Greacen and Oh 1972) that would help turgor maintain root growth. The process has recently been conclusively shown to occur in the shoot also (Jones and Turner 1978), and therefore is not a unique adaptive feature of roots.

It seems more likely that root growth is apparently less affected by stress than is shoot growth, because root meristems are not exposed to the same degree of stress as are shoot meristems. Water potentials in intact roots or in the rhizosphere are very difficult to measure and there is no data on comparative shoot, root, and rhizosphere water potentials. Modeled diurnal courses of leaf- and root-water potentials under conditions of different soil moisture and evaporation demand (Ritchie 1974) suggest that root-water potentials are intermediate between soil and leaf potentials.

Continued root growth in periods of stress is important, as the crop must be able to explore an ever greater volume of soil to maintain even a limited supply of water to the shoot. Resistance to soil-water movement increases sharply as soil-water content declines and the root must literally go to the water.

The soil itself has a large role in determining the rate and the amount of root growth during periods of soil-moisture stress. Rates of root extension have been shown to be related to local soil-moisture conditions (Newman 1966). A relatively high conductivity (for a given soil-water potential) will mean that the bulk soil-water potential can be more easily maintained in the rhizosphere at increased rate of water removal from the rhizosphere. This will favor continued root expansion into deeper layers of the soil and permit in the process greater rates of water supply to the shoot. When the crop is dependent mainly on stored soil moisture, this could be more of an advantage late in the crop cycle than in the early. But where the stress pattern is intermittent and sufficient moisture is expected later, the strategy of maximizing the use of available soil water (stress avoidance) seems appropriate.

Stress Effects on Stomata

One of the major accomplishments of water-relations research in the past decade has been the increase in our understanding of the role of stomata and the nature of stomatal response to a range of environmental influences. This area was well reviewed recently (Turner 1974; Rashke 1975; Jarvis 1976). We shall confine our attention to the effects of changes in stomatal conductance on the crop and on crop environment relationships.

Stomata have been shown by numerous workers to respond to changes in crop-water status, due either to changes in soil-water potential (review by Turner 1974) or to change in transpiration rate (Hall and Hoffman 1976). Changes in stomatal conductance are generally reported to occur over a relatively narrow range of leaf-water potentials once a critical threshold level is reached (Turner 1974), although there are reports of a more gradual or "linear" change in conductance with changing water potential (Biscoe et al. 1976). The actual water potential at which stomata begin to close varies with a large number of factors: species, age and exposure of the leaf, and conditioning of the leaf, among others.

Once the critical level of leaf-water potential has been reached, closure of the stomata reduces the rate of water loss from the crop and reduces the rate of decrease of leaf-water potential. This serves (partially, at least) to protect the plant from the adverse effects of further decline in water potential. The actual mechanism(s) by which the stomata respond to changes in leaf-water potential have not been proven (Rashke 1975), but the logic for the response is clear.

This decrease in stomatal conductance, however, has a number of other consequences for the crop. We shall consider three of these which may be of particular interest to this Workshop: reduction in the rate of transpiration, changes in the crop energy balance, and a reduction in the rate of carbon assimilation.

Reduction in the Rate of Transpiration

Let us consider the simplest model of water movement through the plant as a flux directly proportional to a potential gradient between leaf and soil and inversely proportional to a set of resistances to water movement in the soil and in the plant. Reducing the flux of water through the plant (by a decrease in stomatal conductance) can have one of two effects: (i) it will allow the leaf-water potential to remain constant in the face of either an increasing resistance to water movement in the soil or a decreasing soil-water potential, or (ii) it will permit some improvement in leaf-water potential if the soil-water potential and the resistances to water movement are not changing rapidly. For most soils, however, small changes in water content at low (<5-10 bars) soil-water potentials result in substantial changes in both soil-water potential and hydraulic conductivity (Gardner 1960). Therefore, under stress conditions due to low soil-water availability, the first alternative above seems more probable — i.e., a reduction in transpiration rate results in a stabilization rather than a net improvement in crop-water potentials.

On the other hand, if stomatal closure is due mainly to a very high evaporative demand (i.e., the so called "midday closure") and soil-water availability is adequate to meet normal transpiration rates, then stomatal closure can result in some improvement in leaf-water potential. This in turn will permit the stomata to reopen, producing the characteristic 'midday closure and afternoon reopening' pattern.

In this latter case, the change in stomatal conductance has little effect on the rate of soil-water depletion. This continues at a uniform rate during the midday-closure period (assuming that stomatal conductance is reduced only to the degree necessary to maintain leaf-water potentials at the critical level), as the gradient between leaf and soil remains constant and therefore so does the transpiration flux.

In the former case, in which stomata close in response to decreasing soil-water availability, rates of soil-water depletion are reduced, relative to the potential rates. This probably occurs because in addition to a decreasing soil-water potential, soil hydraulic conductivity is also decreasing. Even though stomatal closure tends to stabilize the potential gradient between leaf and soil, transpiration flux continues to decline because of the increasing resistance in the system.

A reduction in the rate of soil-water depletion may be a very important effect for crops growing on stored soil moisture, such as postrainy-season crops in India. The need in this situation is for the crop to conserve the maximum possible amount of water during the vegetative period for use during the reproductive (grain filling) period. The value of this strategy has been demonstrated using manipulation of crop geometry (Blum and Naveh 1976) and by manipulation of root resistance to water transport from soil to canopy (Passioura 1972). Attempts to do this at the stomatal level, using antitranspirants, have generally been unsuccessful due to toxicity and/or the short life of the antitranspirant materials (Begg and Turner 1976).

Changes in Crop-energy Balance

Changes in the rate of evaporation of water from the leaf surface due to stomatal closure have an immediate effect on crop-energy balance. Because the greater part of the radiant energy falling on the crop is dissipated as latent heat, any reduction in transpiration must increase considerably the energy load on the other avenues for the dissipation of energy — mainly transformation to sensible heat (Begg et al. 1964; Kanemasu and Arkin 1974). In severe stress this process increases leaf temperatures from normal, below ambient, levels to ambient or to levels well above ambient.

There is currently considerable interest in using leaf-temperature air-temperature differences as a way of quantifying crop-moisture stress (Bartholic et al. 1972), and of estimating crop evapotranspiration (Stone and Horton 1974).

Vapor transfer between leaf and air can be simply modeled in a way analogous to that of liquid water flux from soil to leaf, that is, as a flux directly proportional to the gradient in vapor concentration between the inner stomatal cavity and the bulk air and inversely proportional to the sum of the stomatal and leaf boundary-layer resistances (assuming that energy for the evaporation of water is not limiting). The air in the inner stomatal cavity is assumed to be saturated with water vapor, making the actual vapor concentration dependent upon the temperature of the leaf. An increase, therefore, in leaf temperature means an increase in the vapor concentration gradient between leaf and air, and an increase in flux of water vapor out of the leaf. This, partially at least, offsets the effects of stomatal closure on transpiration rate and reduces the expected effect of stomatal closure.

The question of whether or not there are direct effects of heat stress due to changes in energy balance on crops is more difficult. Under water stress conditions in areas of high irradianceand high air temperature, leaf temperatures have been reported to approach levels found in laboratory assays to be directly inhibitory to photosynthesis (Sullivan et al. 1977). Under most conditions, however, heat and drought stress occur together and they are difficult to separate. In addition, resistance to heat and drought stress estimated by membrane integrity tests are frequently correlated (Sullivan and Ross 1978) and it may be reasonable to consider the two as different aspects of the same problem, particularly for stress effects on a metabolic level.

Carbon Assimilation

It is now generally accepted that for all but severe cases, the major effect of stress on photosynthesis is via the effect of stress on stomatai conductance. Field data from a number of sources (reviewed by Begg and Turner 1976) show changes in CO2 exchange under stress follow very closely changes in transpiration or (when it was measured) stomatai conductance. Experiments in a number of crops by Troughton and Slatyer (1969) and Slatyer (1973) have shown that internal or mesophyll resistance (used as a measure of the activity of the biochemical stage of CO2 fixation) was not affected by water stress until stress levels well below permanent wilting were attained.

This reduction in CO2 accumulation is undoubtedly the major cost to the plant for the protection afforded by stomatai closure. A useful way of measuring this cost is by measuring the effects of stress on water-use efficiency (WUE) — the net CO2 uptake per quantity of water transpired during the same interval. An increase in WUE under stress would suggest thatthe crop is benefiting from thetradeoff, and that stomatai sensitivity to moisture stress may be an advantage in certain circumstances.

This approach has been thoroughly reviewed in connection with adaptation to arid and semi-arid zones (Fischer and Turner 1978). These authors make the point that, for single leaves, the effects of stress on WUE would depend largely upon whetherthe primary effect of stress is on stomatai resistance or on internal (carboxylation) resistance, i.e., whether the effects are primarily on transpiration or on CO2 fixation. As indicated above, however, stress effects are primarily on stomatai conductance, at least in the case of moderate short-term stress case. This would suggest the possibility of an increase on WUE under moderate stress.

A theoretical analysis by Cowan and Troughton (1971) however suggests that the reverse may be true in a crop situation. Because of the effect of stomatai closure on leaf temperature and thereby on the vapor-pressure gradient between leaf and air, water-vapor loss may be less affected by stomatai closure than CO2 uptake, unless the internal resistance to CO2 fixation is at least as great as the boundary layer resistance to gaseous diffusion from the leaf surface to the atmosphere. The authors point out that while this may be true for individual leaves, it is less likely to be true for a crop, because the crop boundary layer resistance (to exchange between the crop surface and the atmosphere) increases the effective boundary layer resistance of individual leaves. This hypothesis was verified in a field test with maize (Sinclair et al. 1975); crop water use efficiency was found to be substantially reduced under moisture stress.

Stomatai closure under stress is an essential response, as it serves to protect the plant from the effects of severed desiccation (particularly at a metabolic level) and under certain circumstances may aid in conserving soil waterfor late use. The protection is at a cost to the crop, however. There is no single answer to how serious this cost may be, as it depends upon the probability of the duration and intensity of the stress. Under conditions in which long and severe stresses are probable, there is no alternative to stomatai closure, whatever the cost.

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Modeling Crop Yields Using Climatic Data

R. H. Shaw*

Summary

A soil-moisture model that uses class-A pan evaporation as the estimate for potential evaporation is presented for maize. A crop-stage factor is used to convert this to actual evapotranspiration. If stress occurs, evapotranspiration is reduced, with the degree of reduction depending upon the atmospheric demand and the available soil moisture. A range of rooting depths is required, depending upon the type of weather which occurs.

A stress index, based on the assumption that yield reduction is proportional to the reduction in evapotranspiration from the potential, is calculated. Stress is weighted by thestage of crop development. Special weighting factors, which takeinto account severe stress, are used. This weighted index has been found to be highly related to maize yields under a wide range of weather conditions in Iowa, and should be adaptable to conditions in the semi-arid tropics.

In modeling crop yields by any method, we should always recognize what goes into making up that yield, i.e., the crop factors, the soil factors, and the weather factors. I will be primarily emphasizing weather factors, but the models require crop and soil information. These are not detailed biological models; instead they attempt to describe the water balance for an individual site from day to day. Daily inputs are the shortest time period used. If factors other than the water balance are to be considered, obviously the model would require expanding. Explaining the water-balance effects will require all the time allotted here.

The Model Concept

To start with, let me show you a type of general flow chart for water and soil management-crop growth model. The different segments of this model could each be solved by several different methods; right now we're interested only in the overall concept. I have borrowed this model (Hill et al. 1978) because I believe it presents this concept very well. The flow chart is presented in Figure 1. Later I will go into more detail on how we have approached the problem for maize in Iowa.

We need to start with the environmental setting, i.e., one needs a certain data base from which to start. We need to know certain crop data, soils data, and management data. We need to know the moisture characteristics of our soil, how much water we have to start with, the management practices used, and information about the development and growth of the crop being considered. The management aspect may be simplified by using constant levels of management over areas or years.

Since moisture stress (and other stress factors) will have different effects on the crop at different stages of development, the program must measure or estimate when these stages will occur. The most general model will have a loop which computes these stages of development from weather information, usually temperature data.

A very important part of the model is the amount of evapotranspiration (ET) that istaking place. We usually approach this by using a meteorological measurement to estimate the potential for evaporation then apply a crop-stage conversion factor to give the actual ETfor any stage of development, with soil moisture not limiting. We should break this ET down into soil evaporation and plant transpiration because these change as the crop stage changes.

Next we have to consider soil-moisture

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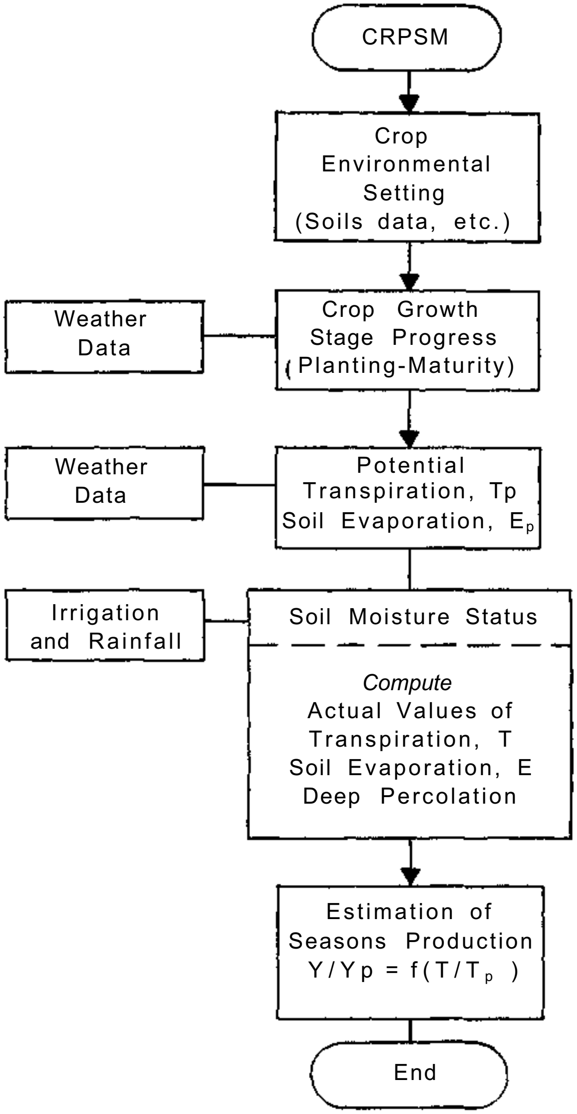

Figure 1. Flow chart of water- and soil-management crop growth model. (After Hill, Johnson, and Ryan).

status. Is it adequate to meet the needs imposed by the atmospheric demand (i.e., soil evaporation, where called for in the model), or transpiration where it is needed? We have to consider the moisture supply relative to the atmospheric demand for water to determine if the supply is adequate. On a very high demand day, there must be more soil moisture present in the root zone than on a lower demand day, if the plant is to avoid stress.

Rainfall, or irrigation water, must be distributed in the soil profile. If runoff occurs, the amount must be estimated, and deep percolation must be considered under certain conditions.

Knowing the daily *water status, we can* estimate the yield reduction due to stress. A function of the type

$$Y/Y_p = f(T/T_P) \qquad (1)$$

is often used. This assumes the yield reduction is proportional to the reduction in transpiration (or evapotranspiration) from the potential. If we are willing to assume the plant cannot regain "lost-yield potential"

$$Y/YP = (T_1/T_{p1})^{\lambda 1} \cdot (T_2/T_{p2})^{\lambda 2} \ldots (T_n/T_{pn})^{\lambda n}$$

in which T_1 = cumulative transpiration (or ET) in growth period i

Tpi = cumulative potential transpiration (or ET) which occurs when soil water is not limiting during growth period i

Y_P = potential yield when transpiration (or ET) is equal to potential.

A model of this type seems to work well in maize, but probably will not work well on our indeterminate type of soybeans. Later periods can compensate for earlier periods (i.e., more pods, or more beans, or bigger beans), so a method must be used which would let the ratio be greater than unity. Differences between these crops *may be* due to the fact that maize tends to have a sink-limiting system, while soybeans have a source-limiting system.

The Iowa Soil-Moisture Stress Model

Now I would like to discuss our corn moisture-stress model. Thetype of approach used is what is important — not the crop. A similar approach could probably be developed for any crop. In computing our stress index for corn (Shaw 1974), we use a soil-moisture model (Shaw 1963) which computes a daily soil-moisture condition. As part of this calculation we obtain an estimate of ET and PET for that day, and use the relation between these to compute the stress index for that day. We have *related* this to yield, using several series of experimental data. We evaluate only soil-moisture stress: if excess moisture occurs this should also be considered.

tion of the relations of the data presented. We use "extractable water" since this is what the plant removed, whereas "available water" usually is defined as the total soil water held in the root zone between field capacity and the permanent wilting percentage (or 15-bar retention) and does not allow for the effect of root distribution on soil water extraction.

What this says is that plants do not remove all the available water from complete root zone under normal atmospheric conditions before the rate of water loss is greatly reduced. The permanent-wilting-point concept assumes the plants are grown under very low demand conditions. Tanner cited one example for a Plain-field sand which has extractable water of 40 mm in thetop 100 cm, but has available water of about 58 mm. The fraction of extractable water left when T/Tmax decreased below unity was 0.30, or 28 mm had been extracted. If the same amount (28 mm) were removed of the total available before the transpiration rate decreased, 52% of the total available would remain. On that basis, thedata in Figure3, using available water, are in agreement with Tanner's value of 35% extractable water. We are saying about thesamething, but using different terms of reference.

Our field experiments have also shown a sensitivity to day-to-day demand. On a high-demand day, plants have shown extensive wilting. On a subsequent day with medium atmospheric demand (and no water added), there was little or no wilting, and none if it was a low-demand day. On a following day with high demand, the plants were again wilted. For that reason, we have used three different curves to represent the different types of demand days. A day with pan evaporation > 7.6 mm is considered a high-demand day; 5.1 to 7.6 mm a medium day; < 5.1 mm, a low-demand day. The relationship (Fig. 3) is used during the period that roots are growing to deeper depths. After silking, when we assume there is little further root development, a somewhat different relationship is assumed, with the curves displaced to the left from these shown. These relationships have been shown to predict soil moisture quite well under Iowa conditions.

To calculate evapotranspiration under stress conditions (STET), the following factors are multiplied: Pan evaporation x ratio for crop development (Fig.2) x stress factor (Fig. 3).

When evapotranspiration is reduced because of stress, we allowfor up to 2.54 mm soil surface evaporation to take place from the top 12.7 cm of soil. STET plus soil evaporation cannot be greater than nonstress ET.

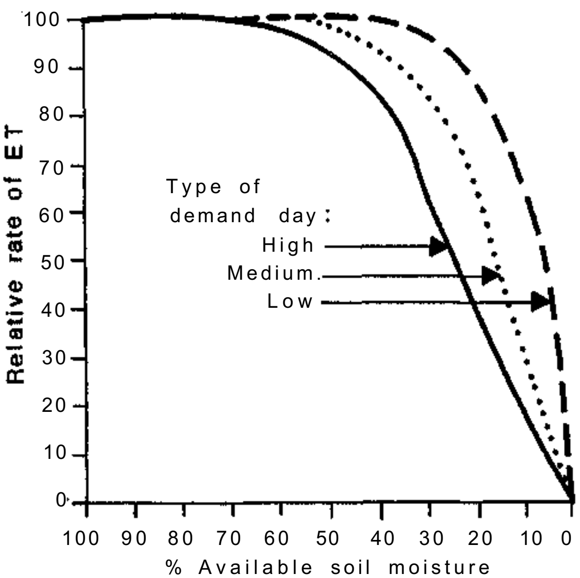

Figure 3. Relative evapotranspiration rates for different levels of atmospheric demand.

Stress Index

We now have the basis for our current stress index (SI)

$$SI = 1 - \frac{\text{Actual ET + Adjusted sfc. evap.}}{\text{Potential ET}}$$

It was not believed that surface evaporation (under STET conditions) is as effective at reducing stress as is transpiration, so limits were put on its use.

a. Under high atmospheric demand (Pan evap > 7.6 mm) and STET < 0.10 cm, use zero evaporation.

b. Otherwise, add all evaporation when it is < 0.13 cm and add 0.13 when evaporation is > 0.13 cm.

If actual ET, or actual ET + adjusted surface evaporation, is equal to potential ET, there is no stress for that day. Stress is equal to the reduction in water loss for that day, compared to the potential. An actual-to-potential ratio of 0.60 would mean a stress index for that day of 0.40.

We also believe that the stage at which this stress occurs is important and has different degrees of effect on the crop. A number of researchers have worked on this. Based on their results, the weighting factors shown in Table 2 were determined. A period of 85 days is used, covering the period from 40 days before silking to 45 days following silking. Stress-index values are summed and weighted by the 5-day periods shown. This assumes stress has no cumulative effect, which has been true under some experimental conditions (Mallett 1972). However, our field data indicate that extreme stress can have greater effects. We've added three additional weighting factors:

a. If the stress index fortwo or more consecutive 5-day periods is s ≥ 4.50 (max of 5.0 possible), an additional weighting factor of 1.5 is used for each period.
b. If more than one of the three 5-day periods just before silking has an index > 3.0, these periods are multiplied by an additional 1.5. This takes into account the effect (reduced pollination) of relatively severe stress just before silking.
c. If the period before and the period after silking have a stress index ≥ 4.50, a crop failure is designated. Under these conditions, fertilization apparently does not occur and silks do not emerge.

Table 2. Relative weighting factors used to evaluate the effect of stress on maize yield. Periods are consecutive 5-day periods prior to and following silking.

Period	Weighting factor	Period	Weighting factor
8 before	0.50	1 after	2.00
7 before	0.50	2 after	1.30
6 before	1.00	3 after	1.30
5 before	1.00	4 after	1.30
4 before	1.00	5 after	1.30
3 before	1.00	6 after	1.30
2 before	1.75	7 after	1.20
1 before	2.00	8 after	1.00
		9 after	0.50

Use of Stress Index

How well has this done? Let me show you some results. Two items are evident from Figure 4 — which plots data for a northwest Iowa location the driest part of the state. The weighting factor for extreme stress properly adjusts the one data point. The squares indicate years when there was excess moisture present in the spring. We've found under these conditions that our estimated yields are higher than those that actually occurred, i.e., excess wetness caused a yield reduction. Figure 5 is from a location in central Iowa. It did not show the severe stress occurring, but notice the number of years when excess moisture occurred. We do not estimate the effect of excess moisture in our procedure, but it must be kept in mind if all environmental effects are to be considered.

Problems in Recent Years

In developing a procedure of the type that has been explained, a wide range of weather conditions is necessary to evaluate it properly. In 1976 we had a very dry spring, and this encouraged deeper rooting than usual. In late July we took soil-moisture samples and found little or no available moisture down to 152 cm, yet the crop was still in fairly good condition. Obviously, it must have been getting moisture from deeper depths. The first soil moisture-stress

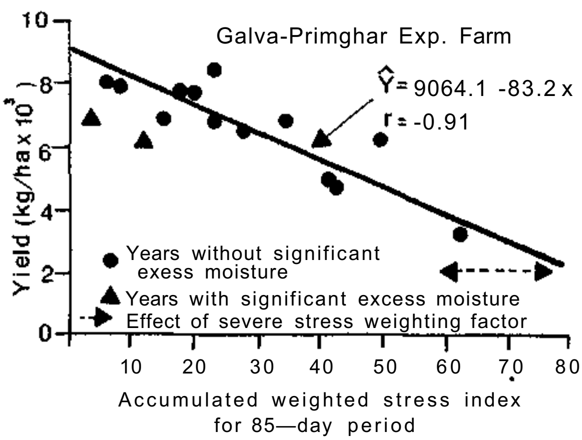

Figure 4. Relationship between weighted stress index and maize yield in northwest Iowa.

calculation showed most of the yield estimates close to the dashed line (Fig. 6), with a few points (triangles) near the 1-1 line. Other information indicated that at most sites maize was probably rooted to about 213 cm. The program was rerun using a rooting zone of 213 cm rather than 152 cm for all data points that had not reached saturation of the 152-cm profile in May or June. The triangles represent the points which did, and only the 152-cm profile was used for these sites. The final results were very good, indicating that under different conditions, different rooting depths must be used.

In 1977 we ran into an unusual stress condition before silking. The points shown as open circle (Fig. 7) all had stress-index values >3 for more than one of the three, 5-day periods just prior to silking. This situation had occurred at only 13 sites in 23 years of prior sampling (450 site years). The additional weighting factor just prior to silking was added because of this severe stress and it adjusts the points to around the 1-1 line. The labeled (solid circle) data points in the figure almost reached this condition. These locations all have very heavy subsoils, and maize growing here apparently was not ableto respond as well, in comparison with that growing on the better soils, to the rapidly deteriorating moisture conditions. It points out that understanding the difference in soils is important, and that not all soils should be treated the same.

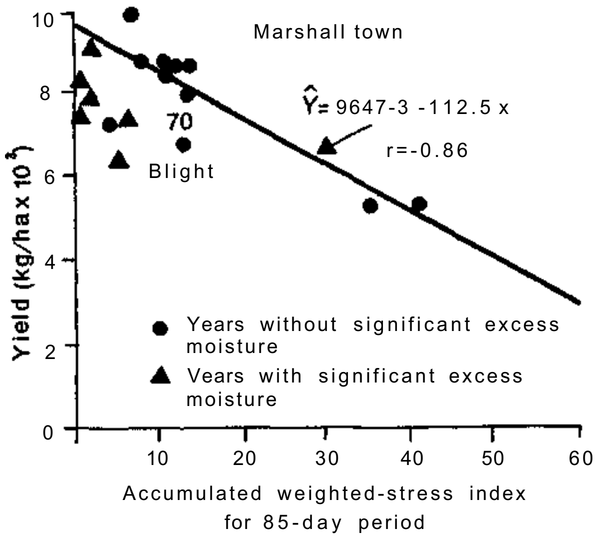

Figure 5. Relationship between weighted-stress index and maize yield in central Iowa.

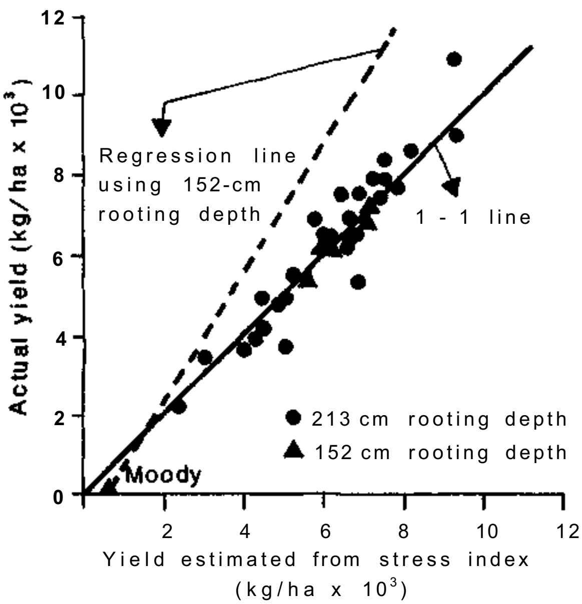

Figure 6. Predicted and measured yield in 1976.

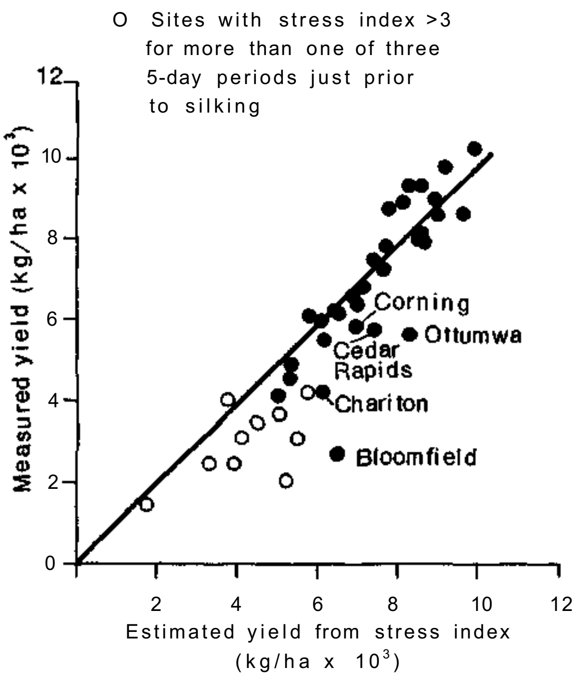

Figure 7. Predicted and measured yields in 1977.

An approach like this should be adaptable to the semi-arid tropics, once the necessary experimental data for these climatic conditions are available.

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Use and Requirements of Agrometeorological Data for Quantifying Crop-moisture Stress and Needs

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Summary

The terms "crop-moisture need" and "stress" are defined and factors affecting them are detailed, as one criterion for quantifying crop moisture stresses for irrigated and rainfed crops. The limitations and use of the concept of potential evapotranspiration are discussed; methodologies for quantifying moisture stress for rainfed crops and dry/and use-planning are outlined. Timing of irrigation to avoid moisture stress in various crop phases is examined. Agrometeorological data requirements in certain critical areas and scope of further studies are indicated.

The "Transpiration Requirement (TR)" constitutes the minimum crop-water need and is provided by root-zone soil moisture. TR is affected in all stages of crop development by the evaporative demand of air (ED). TR nearly equals ED from the stage of ground shading to maturity. From germination to the groundshading stage, TR is less than ED and the ratio of TR/ED is influenced by the leaf-area index/ fractional ground cover. During maturity TR is dependent on the nature of crop physiology (Tanner and Lemon 1962; Gates and Hanks 1967; Ritchie and Burnett 1971; Venkataraman et al. 1976a; Venkataraman et al. 1976b; Sarker et al. 1976; Subba Rao et al. 1976).

The actual transpiration (AT) of the crop, expressed as equivalent depths of water per unit ground area, is at all crop stages influenced by the quantity and ease of availability of root-zone moisture in the range from field capacity to permanent wilting point. For a given crop stage and ED, the rate at which transpiration can proceed when root-zone moisture is at field capacity may be termed "Potential Transpiration (PT)." A water stress may be said to occur when the rate of AT begins to fall off sharply from PT. In the available soil-moisture range, the point at which a sharp drop in AT occurs may be termed the Critical Moisture Level (CML). Ease of soil moisture availability (and hence the value of CML) is affected by factors such as soil types, level of evaporative power of air, and the amount of water the crop can draw upon from its root zone (Baier 1965). The last quantity, termed the "Root Constant (RC)," varies with crop types and stages. The variation of RCfor a given crop and crop stage is thought to be small in various soil types (Fleming 1966) on account of the compensating effect of root proliferation and unit volumetric content of available root-zone moisture. Generally there is a reduction in soil moisture availability with an increase in (1) the clay content of the soil, and (2) the evaporative power of air, while an increase in RC tends to delay the incidence of CML (Holmes 1961).

Nontranspiratory Components

When moisture falls and moves into the soil surface, either as irrigation or as rain, evaporative loss becomes inevitable. This combined loss is called Evapotranspiration (ET). For moisture-stress quantification, it is necessary to separate out the evaporation component of ET (Monteith 1965; Black et al. 1970; Goltz et al. 1971; Burn et al. 1972; Ritchie 1972; Tanner and Jury 1976).

The crop-field moisture losses, such as surface runoff and percolation beyond the root zone are controllable for irrigated crops but are

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weather dependent for rainfed crops. Again, the contribution of rainfall to crop-water needs is enhanced for a standing crop, and even light rainfall can be effective (Owen and Watson 1956; Glover and Gwynee 1962).

Need for Agrometeorological Approach

Studies in which crop-water need, soil-moisture storage, and crop-water stress are considered to be solely weather-determined can only provide comparative estimates of moisture stress in space or time. For quantification of moisture stress, of either irrigated or rainfed crops, neglect of the crop or soil factors is not, a priori, permissible—especially in the semi-arid tracts.

Criteria for Stress Quantification

A perusal of the investigations reported in the references cited previously is helpful in spelling out the criteria for quantification of crop-moisture stresses. For irrigated crops the parameters required to determine incidence of moisture stress are: (1) permissible amounts of moisture depletion in rootzone, and (2) thetime interval over which this would occur. In the case of rainfed crops, moisture stress can be quantified by finding out the march of the ratio of AT/PT on a short-period basis, thereby locating the periods and duration of occurrence of sub-potential transpiration and assessing the feasibility of crop survival in the stress periods so delineated.

Potential Evapotranspiration

The Concept

With a short green active ground-shading crop growing on a soil with adequate root-zone-moisture the water need nearly equals the ET loss. The water need is termed "Potential Evapotranspiration" (PET). PET can be stated as representing the upper limit of the crop-water need and is of obvious importance in moisture-stress quantification.

Computation of Climatological Averages

Penman (1948) has outlined a sound theoretical approach to estimate PET; he has also postulated an empirical method to obtain PET from more simple data, a method that has been used extensively. For computation of PET, Penman (1956) has advocated the testing of his theoretical approach, instead of relying on the repetitive use of his empirical formula.

The "testing" of Penman's approach has been handicapped by lack of observational data on (1) net radiation corresponding to an extensive green cover, and (2) low-level (2-m) wind runs and difficulties in calibration of the constants in the wind-function term. Monteith's classical work (1964) therefore assumes significance, leading as it does to the use of the averages of the range of experimentally determined values of various forms of resistance to the movement of water from the soil through the plant to the air, in place of the wirrd function. Venkataraman (1977b) has pointed out that pyrgeometric estimates of the nocturnal long-wave flux would correspond to that of a crop cover envisaged for estimating PET, and has shown that the average of the ratios of net to back radiation obtained from pyrgeometric measurements of atmospheric long-wave flux are applicable, for climatological purposes, to the day as a whole.

A combination of the postulations of Monteith (1964) and Venkataraman (1977a) should provide reasonably accurate estimation of climatological values of PET at radiation measurement stations having 10 or more years of shortwave radiation and pyrgeometric data.

Computation for Operational Purposes

For many climatological applications, use of single values of monthly PET may be permissible because of small interannual variations. However, for operational purposes, daily values of PET would be required. To achieve this, the mean monthly climatological values of PET have to be empirically related to the average values of a climatological parameter that is and/ or can be routinely measured. Of the various parameters that have been considered for this purpose (solar radiation, net radiation, pan evaporation, and air temperature), evaporation from standard shallow mesh-covered pans (EP) is the most suited, as pan data is an integration of the energy, wind, and vapor pressure-deficit factors — which also control the PET quantum. Calibration of the ratios of climatological estimates of PET to average values of EP, on a monthly and regional basis, would make feasible the use of EP data as an operational tool for quantification of crop-water stresses.

There is an urgent need for making reasonably sound estimates of monthly PET and working out empirical relations between PET and other climatological parameters such as EP for as many stations as possible in the Semi-Arid Tropics (SAT).

Feasible Uses

Taking PET as the optimum water need works only with crops that are in the vegetative phase of development and that shade the ground fully. In the SAT there are considerable areas in which cash crops are raised with irrigation. These crops pass a good fraction of their life cycle in the rainy season and are often at the ground-shading stage at the start of the rainy season; they enter the maturity phase after the cessation of rains. Reasonably good estimates of water-stress quantification for such crops can be made through a simple budgeting of weekly rainfall against weekly PET after allowing for soil-moisture storage as appropriate to the crop under consideration.

In high-altitude regions of the SAT, plantation crops generally have field-capacity moisture status when the rains cease. It is easy to determine this quantum from conventional soil-moisture measurements. Budgeting of the stored soil moisture plus any incidental rainfall against PET can be used (Willat 1971) to gauge the time of onset, duration, and severity of moisture stress for plantation crops.

Perennial orchard crops are also of importance in SAT areas, as the water needs of these crops are considerably less than PET (due to the presence of stomata mostly on the underside of the leaves and their relatively high RC values). Budgeting of rainfall versus the reduced PET need and appropriate RC values could be used to quantify moisture stress for perennial orchard crops.

Feasible Improvements

In the above three types of studies, the quantification can be improved by (1) allowing separately for evaporative depletion of rainfall or stored moisture at rates equal to ED at the soil surface (EDS), (2) budgeting of available rainfall/soil moisture against PT, and (3) providing for appropriate reductions in AT when available rainfall/soil moisture is less than RC. For example, EDS for a ground-shading crop may be 20 ± 5% of PET (Hanks et al. 1969; Ritchie and Burnett 1971; Burn et al. 1972; Venkataraman et al. 1976a, 1977), and hence PT would be80 ± 5% of PET. Similarly, reasonable assumptions regarding ease of soil-moisture availability in various soils and for various evaporative demands can be made to fix values of likely AT for one filling of the root zone to field capacity.

Moisture-Stress Quantification for Dryland Crops

Effective Rainfall

Rainfall that is not lost by way of evaporation, surface runoff, and percolation beyond the crop-root zone may betermed Effective Rainfall (ER), which provides the sustenance moisture for rainfed crops. For crops seeded early in the season, assessment of evaporative depletion only may suffice in the presowing period. However, compared to bare soil, there would be significant additional accretions of effective rainfall when the crop reaches the ground-shading stage. This would comeaboutthrough: (a) reduction in evaporative depletion via the soil surface and reduction in surface runoff, (b) foliar interception of rainfall, and (c) increase in moisture-storage capacity provided by the transpiratory withdrawal. The influence of the crop factor on evaporative depletion of rainfall till the crop reaches the ground-shading stage may be considered as negligible. Again, from the ground-shading crop stage the reduction in surface runoff due to the crop cover may be offset by the enhanced moisture status of the soil.

Thus, for assessing moisture adequacy, the appropriate estimate of ER would be that relating to: (1) bare ground in the crop-establishment phase and (2) a soil surface fully shaded by foliage, from the ground-shading stage onwards.

Evaporative Loss

Under the type of rainfall distribution that occurs in SAT areas, sophisticated and complex methodologies may not be necessary to account for evaporative losses in terms of PET and evaporable moisture on days following a wetting (Ritchie 1972). Hence, assessment of evaporative depletion of rainfall appears more straightforward. For example, total daily falls of rain that are less than PET may be ignored, and evaporative depletion in a wet spell following an amount of rain greater than PET may be allowed for at PET rates till no moisture is left for liquid-phase evaporation or till the accumulated storage exceeds the moisture capacity of the evaporative desiccation layer (Venkataraman et al. 1973). In the former case, the process is repeated when another wet spell comes along. In the latter case, the accumulated total in excess of the moisture capacity of the evaporative zone is put down as soil-moisture storage on that date and the process recommenced with the above moisture capacity as the input for evaporative depletion in subsequent days. If one uses the EDS values instead of PET values one can get estimates of ER relating to a ground-shading crop.

Thus for the SAT areas, data are needed on(1) the maximal quantity of evaporative depletion per wetting of the surface-evaporative zone of 15 cm or so under low, medium, and high evaporative demands and (2) the factorial evaporative potential in relation to PET at a fully shaded soil surface — under various crops, layout geometry, and soil types.

Surface Runoff

The question of accounting for surface runoff is more difficult, as this quantum would be highly location specific. However, where experimental data on surface runoff under various crop covers, soil slopes, and soil types are available, an examination of these in relation to daily totals of rainfall may enable one to fix criteria for allowing for surface runoff (e.g., Kanitkar et al. 1960, Venkataraman et al. 1973) for given types of slopes and covers of soils. Russell (1978) had observed surface runoff to occur on days on which daily rainfall totals or peak rainfall intensities exceed the moisture-holding capacity of the surface 30-cm depth of soil. The latter quantum would depend on the moisture status of the soil at the onset of rainfall.

Hence, in the SAT areas, there is an obvious need for publication of available data on frequencies of occurrence of daily rainfall totals and peak-rainfall intensities in various ranges; for studies on the relationship between daily and peak-rainfall intensities; for collection of data on surface runoff under various soil covers, types, and slopes; and for augmentation of a network of recording raingauges.

Moisture Needs

For quantifying moisture stress, it is necessary to determine the durations in which the amount and distribution of effective rainfall (estimated as detailed above) would have been able to maintain crop transpiration at potential and subpotential levels from the actual/propitious date of sowing. For this, information on the progression of transpiration need of the crop is required. Before dealing with the phasic moisture requirements of crops, it is necessary to consider moisture availability and requirements for sowing.

Moisture Needed for Sowing

In this, one needs to consider only evaporative depletion of rainfall and availability of small storages to tide over postemergence dry spells. For example, wet weeks in which the total rainfall exceeds PET or there is a moisture storage of 15 mm can be considered suitable. (Fitzpatrick and Nix 1969; Venkataraman 1977b). For meaningful application, these studies must take into account the frequencies of occurrence of certain situations — e.g., a wet week and a dry week being preceded or succeeded by a wet week. These data, expressed in terms of conditional frequencies or probabilities (Venkataraman 1977b; Virmani et al. 1978), are of great value in estimating the probable best date of sowing.

Moisture Needed for Crop Establishment

Experimental data on consumptive use of

rainfed crops, when corrected for evaporative depletion of daily falls of rains, as in the case of bare soil, can give a measure of the transpirational consumption of the crop during the establishment phase. Alternatively, when consumptive-use data for the same crop under irrigated conditions are available, the transpirational consumption can be worked out by allowing for a fixed quantum of evaporative depletion in the interval between irrigations. The transpirational consumption can be related to a measure like PET in order to obtain the ratio of relative transpiration. The data on relative transpiration could then serve to estimate the transpirational need of the crop in the establishment phase for any given crop-weather situation. It is obvious that this will require reliable daily data on ET losses, which only careful lysimetry can provide.

Moisture Needed from Ground-Shading to Maturity

Gauging the transpirational need of the crop during the ground-shading to maturity stage is relatively easy, as one needs only to evaluate the component of evaporative potential at the soil surface in PET. As mentioned, this information is available for typical crops and is adequate; the transpirational need of a ground-shading crop would be80 ± 5% of PET.

Moisture Needed During Maturity

Under normal management, dryland crops enter the maturity phase after cessation of rains. Consumptive-use data for this phase are free of intermittent spurts in the evaporative losses. However, the transpiration need in this phase would, as already pointed out, depend on the physiological nature of the crop. Determination of the ratios of relative transpiration for this phase should be done for specific crop types.

Computation of Actual Transpiration

In any crop phase, estimating the time of incidence of the moisture stress from a budgeting of effective rainfall against transpiration needs is facilitated by the fact that in the rainy season (which generally covers the vegetative crop phase) the evaporative regime is more or less equable. This, in turn, means that the pattern of extraction of available soil moisture for a given soil type would be the same in all phases. This pattern can be rationally characterized and used to locate the commencement and end of the stress periods.

Fitting of Crops to Rain

The methodology suggested above is applicable to crops of given growth rhythms and root constants. The above type of agrometeorological analyses, when carried out for a set of root-constant values, can help locate the favorable times and duration for completion of the various crop phases and hence of feasible crop-life period and du ration for each value of RC. It is then agrometeorologically feasible to specify the crop type that — in the light of its life duration, growth rhythm, and root constant — would have adapted itself to the moisture stresses generated under a given rainfall distribution.

Such analyses carried out on a year-to-year basis can be used to (1) determine the most desirable value of root-zone moisture capacity and (2) work out the frequencies of occurrence of various ranges of crop-life durations. This can in turn be used to plan cropping patterns that would serve to alleviate the risks of moisture stresses due to rainfall variations in a particular area.

Rainfall Zoning

Analyses of the above type of analyses require delineation of homogeneous rainfall zones in SAT areas. Probabilistic estimates of assured weekly rainfall amounts can be used (1) to demarcate rainfall zones (Biswas and Khambete 1977) and (2) to (a) locate time of start of the crop season, end of the period of effective rains, and midseasonal dry spells; (b) indicate end of the crop season; and (c) delineate agronomically homogeneous areas (Venkataraman 1978). Various techniques to estimate assured weekly rainfall amounts on a probability basis have been advocated (Thorn 1958; Gabriel and Neumann 1962) and are being adopted. There is a need to compare estimates obtained by various methods, examine features revealed by them at typical locations, and select the most suitable and least complicated method to work on rainfall reliability, especially with a short data series.

Irrigation Timings

To prevent moisture stress in irrigated crops and maximize water-use efficiency, correct amounts of water have to be applied at correct intervals of time. Quantification of the optimum irrigation need over given intervals of time is easier. The question of irrigation timing/interval becomes important, not so much for water-conservation, as for maximization of the command area and distribution of crops in it.

For scheduling the amounts and intervals of irrigation, the daily ratios of relative evapotranspiration (ET/PET) and the quantum of available water the crop can draw upon in various growth stages are needed. The latter information is extremely difficult to obtain, but can be avoided by adopting the following reasoning:

In regard to the time of incidence of crop-moisture stress following an irrigation, it may be argued that the influence of fractional ground cover would be of secondary importance. Such influence could be ignored if the ratio of relative transpiration [for any given crop stage(s)] is the same as of relative water availability, which may be defined as the ratio of the actual root constant to the maximum value pertaining to a fully developed croproot system. Allowances for influence of fractional ground cover can be made if the progressive relationship of relative transpiration to relative water availability can be established. For example, many crops reach the groundshading stage at a leaf-area index of 3 (Monteith et al. 1965; Ritchie and Burnett 1971), the maximum leaf-area index may be as high as 5. If there is an increase in the root-constant value between the ground-shading crop stage and the attainment of full leaf canopy, the irrigation interval can be extended if the evaporative regime continu es to be the same.

Such information would also be useful in determining the time of incidence of crop-moisture stress at any stage of the crop, using computations of the maximum root constant at potential transpiration rates in fully established stands. The latter is easier to do, as the relevant data can be more readily obtained.

Agrometeorological Data Requirements

From the above review of factors involved in, and the feasibility of, quantification of crop-moisture stress and needs, it appears that the following studies/data acquisition would be useful in SAT areas:

1. Standardization of the methodology for estimating occurrence of specific/assured rainfall amounts over weekly periods at various probability levels.
2. Development of agrometeorological criteria for use of rainfall probabilities in demarcation of homogeneous rainfall zones.
3. Computation of climatological values of PET at all radiation-measurement stations and use of the same to develop empirical formulae based on simple meteorological parameters for local and operational applications.
4. Acquisition and compilation of data of total nonvapor-phase evaporation losses per wetting of the surface 15 cm in different soil types and under low, medium and high evaporative demands.
5. Acquisition and compilation of data on the fraction of the evaporative component in PET for typical crops and crop layouts.
6. Augmentation of the network of self-recording raingauge stations.
7. Publication of data on frequencies of occurrence of specified amounts of daily total rainfall and peak-rainfall intensities.
8. Acquisition of concurrent data on surface runoff and daily and peak-rainfall intensities.
9. Collection and/or analysis of available daily evapotranspiration data and development of simple models for screening out the evaporation component of the ET losses, especially under incomplete crop cover and inadequate inputs of soil moisture.
10. Acquisition of data on progressive changes in relative transpiration in relation to relative moisture availability.

11. Testing of models on the accretion and use of effective rainfall.
12. Development of methodology for fitting crop types and crop phases to given rainfall-distribution patterns, and use of the same for dryland-use planning to mitigate the influence of periodic variations in rainfall.

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Research on crop Water Use and Drought Responses in East Africa

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Summary

A research project aimed at development of cropping systems for the marginal rainfall areas of Kenya is introduced, together with a brief review of pertinent research in East Africa. The phrase "sequential research on limiting factors" is used to characterize the research concepts and approach taken in the project. A broad relationship between potential yield of maize and energy available for growth, using Class-A pan evaporation as the integrator of energy, is fitted within the weather pattern at Katumani to show yield potentials as related to planting dates at that site.

Modification of yield potentials of Katumani maize by reducing plant population is shown next, using experimental data developed in the project. The final step, in two parts, consists of estimating water requirements, which (like yield potentials) are related to evaporative conditions and modified by plant population, followed by arbitrary assignment of a "yield reduction ratio" which characterizes the relative yield loss rate of Katumani maize with increasing ET deficit due to insufficient rainfall.

Nine water production functions are estimated, showing yield expectations at varying levels of ET_A. for Katumani maize planted on three dates that accord with the rainfall pattern, and at three plant populations on each planting date. The family of water production functions offers clear guidance on optimal planting dates and plant populations in accordance with anticipated crop water supply. Crop yields are also predicted.

It is concluded that development of water production functions of the type described for a number of crops suited to a given area, together with development of methodology for estimating expected crop water supply, would pro vide the basis for selecting among cropping alternatives, and formulating optimal cropping systems from the technical standpoint. It would also provide the data required to carry out economic analyses, which, when considered together with social constraints, could serve to modify final cropping system recommendations.

Until the early 50s, the main effort in agricultural production and hence agricultural research in East Africa was devoted to industrial crops like coffee, tea, cotton, and sisal. Tea presented no problems as it is grown on fertile, well-watered highlands. Most coffee estates were also located in areas of sufficient rainfall, and similarly, the lowland areas with high convective rainfall proved appropriate for cotton. For those expatriate farmers who could not get into the highlands, sisal proved well-adapted to the drier savanna regions. For these individual crops, therefore, the major limiting factors were diseases and maintenance of soil fertility.

With the large profits to be gained from coffee production, farmers started to extend coffee production to the somewhat drier areas where supplemental irrigation could be applied from nearby rivers. At this point, the cost of such irrigation was of little consequence and the farmers applied quantities they judged (from experience) to be adequate. As irrigation costs increased, coffee farmers became interested in better methods of irrigation control and studies were initiated on the variation of soil moisture in coffee plantations in relation to rainfall (Pereira 1957). It was then soon realized that

* USAID/USDA/KARI research project, Muguga, and Kenya Agriculture Research Institute, Mugaga, Kenya, respectively.

total rainfall alone was not a sufficient criterion for determination of suitability of an area for a given crop, and intensive studies were initiated to estimate potential evaporation as an aid to the determination of effective rainfall or available water. The work of Penman (1948), Thornthwaite (1948), Blaney and Criddle (1950), and many others was therefore adopted in East Africa and a network of evaporation pans and agrometeorological stations was quickly established. By the mid-1960s sufficient data had been accumulated to facilitate the production of thefirst maps of potential evaporation (Penman E_0) for the whole of East Africa (Dagg et al. 1970).

While the hydrometeorological studies were in progress, it was recognized that crops did not necessarily transpire at the potential rates as defined by Penman (1948), and parallel research work was set up to estimate the actual water balance of a field crop. This work would aid in determination of crop-water requirements. The recognition of the variation of crop-water requirement with stage of development (ground cover and rooting depth) opened the way to a rational approach to the whole concept of matching crops, including long-season crops like maize and sorghum, to environments described by effective rainfall and soil water storage characteristics (Dagg 1965). These studies also had an impact on maize breeding in Kenya where breeders soon produced short- and medium-maturity maize varieties to fit within periods of available water in different ecozones. The precision required in the water balance could not, however, be easily achieved in monitoring field soil profiles, in spite of the improvements in techniques of soil-moisture measurements from gravimetric sampling through soil-moisture resistance units to neutron-scattering techniques. Research work, therefore, started on the design and installation of weighing lysimeters (Glover and Forsgate, 1964; Forsgate et al. 1965).

Successful development of a simple, inexpensive hydraulic weighing lysimeter has facilitated in the last ten years determination of crop water-use patterns for sugarcane (Blackie 1969), maize and beans (Wang'ati 1972), tea (Dagg 1970) and, to a limited extent, bananas (Nkedi-Kizza 1973). Most of these experiments were, however, designed to provide general water-use patterns under conditions of optimum soil-moisture availability and good soil fertility. The expectation was that if accurate estimates of growth stage-related crop-water requirements, ETM, could be related to the potential evaporation or atmospheric demand, Eo, which is a climatological parameter, then not only could crops be matched with effective rainfall, but also this would lead to a more rational determination of supplemental-irrigation requirements and hydrological implications for changes in land use.

In recent years, it has been recognized that for crop water-use studies to be meaningful, the yield response of the crop to water deficits must be known. Observations also showed that, for maize, severe water deficits at the fertilization and grain-filling stages resulted in marked yield reduction. The concept of crop water-use efficiency, which combines studies of crop-water use and drought response, has therefore gained prominence, especially when dealing with selection of crops for adaptation to marginal rainfall areas. It is known that different varieties of a crop have varying degrees of drought tolerance in relation to survival and to yield reduction. Current and future research is therefore oriented to elucidating this phenomenon and its use in the development of cropping systems.

The current project on development of cropping systems is aimed at rainfed crop production on small farms in the marginal rainfall areas of Kenya. It began in October 1977 and is being carried out by the Agriculture Research Department of the Kenya Agriculture Research Institute. Scientists and funding are being provided in the initial years of the study by USAID. Details of the background, functioning, and goals of the project are set forth by Stewart and Wang'ati (1978).

This paper utilizes a sequence of sixfigures to illustrate concepts and research approaches of the project.[1] The intent of the figures is outlined briefly here, after which they will be discussed in detail. Figures 1 and 2 show broad relationships between climate (available energy) and potential yields of cotton and alfalfa. Such relationships may be transferable from one place to another, even between countries. They

1. Some symbols and definitions used are explained at the end of this paper.

are the starting point for development of site-specific water-production functions to be used to guide crop management for optimal use of available water, and to predict crop yields in accordance with water expectations. Such functions are illustrated in the final figure but first there are intermediate steps to take.

Figure 3 combines data from a coordinated research effort at four sites in the western USA (Stewart et al. 1977a) with local data developed in the current project to suggest a climatic limitation on maize yields, applicable to the USA and East Africa and elsewhere. The authors wish to emphasize at this point that Figures 3, 4, and 6 represent research in progress, and are thus primarily illustrative — i.e., they incorporate all available data and the operative research concepts and assumptions, but are not presented as definitive in quantitative terms.

Figure 4 illustrates the adaptation of the broad relationship in Figure 3 to a specific site, the Katumani Dryland Farming Research Station, Machakos District, Kenya. Three maize experiments have been completed under the project, and fourth will be harvested in November, 1978. Figure 4 emphasizes the importance of planting date to potential yield.

Figure 5 shows an experimentally determined relationship between yield of "Katumani maize" and plant population. Katumani maize,

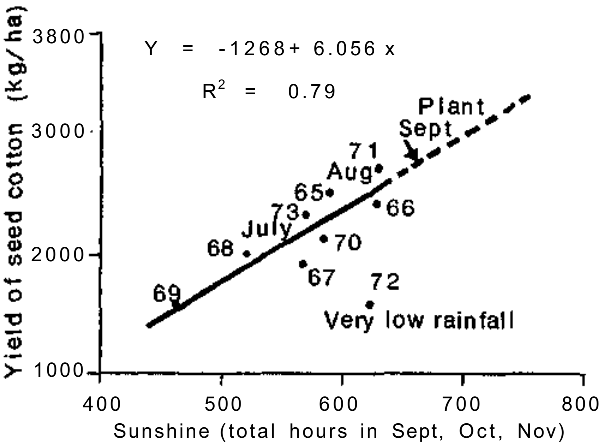

Figure 1. Yields of mid-July planted seed cotton versus Sept-Nov sunshine hours in the Managua-Granada area of Nicaragua, 1965-1973 inclusive.

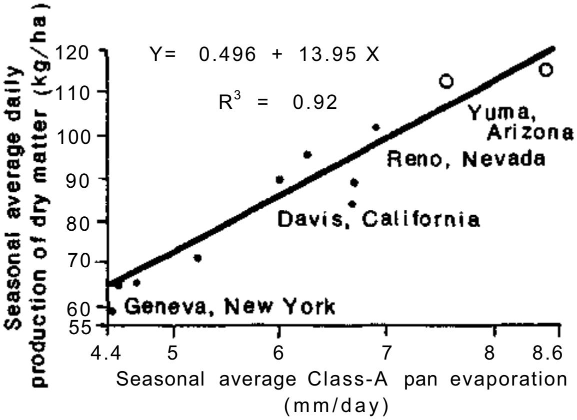

Figure 2. Broad correlation between rates of Alfalfa production and pan evaporation. Well-managed first- and second-year stands with adequate water. Four climate zones, 11 years, six locally adapted varieties.

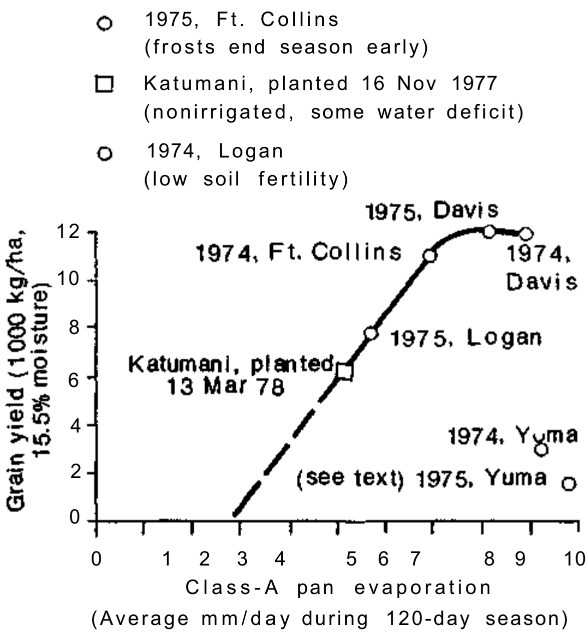

Figure 3. Suggested climatic limitation on maize yields, with weather integrated by class-A pan evaporation. Locally adapted maize hybrids, well-managed with adequate water, except as noted.

with maturity of 110-120 days, is a composite bred and selected in Kenya for marginal rainfall areas. Figure 5 emphasizes the important role plant population plays in determining yield potential in field plantings.

Hopefully, by this time the approach being taken is becoming clear. It might be termed "sequential research on limiting factors." In marginal rainfall areas, water is commonly termed the most limiting factor. Our approach would place it instead as the final limiting factor in a succession of limiting factors — beginning with available energy, then becoming site specific in the form of planting date, then considering plant population, after which other factors are considered as required, e.g., soil fertility, salinity, weeds, pests and diseases, etc., and finally, water availability. At each step, all factors not yet considered are taken to be at the optimal level.

Through consideration of all possible yield-limiting factors is beyond the scope of this paper. Figure 6 moves directly to the water factor. First it shows potential yields of Katumani maize planted in the Katumani area on three different dates at three different population levels. Next, relationships from recent research (Stewart 1972; Stewart et al. 1973; Stewart and Hagan 1973; Stewart et al. 1977) are used to calculate water requirements to attain potential yields in each of the nine cropping situations, and to suggest rates of decline of yield with declining water availability. In keeping with what was said in the preceding paragraph, all yield levels shown in Figure 6 (including all points along the lines representing inadequate water) are predicted on the assumption that fertility and other factors not evaluated are at levels which permit the yield in question to be produced.

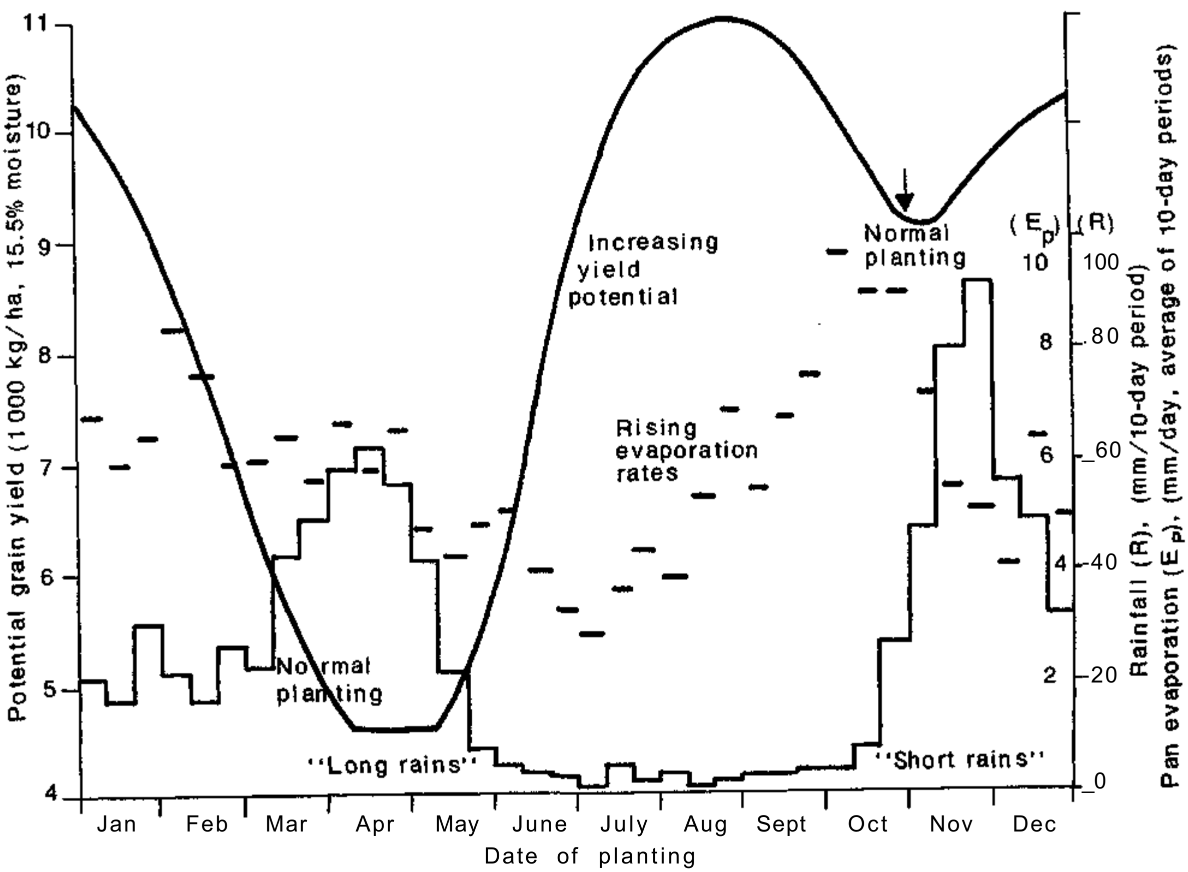

Figure 4. Suggested effects of growing-season evaporative conditions on potential yield of Katumani maize, relative to planting date (Preliminary data. Additional study required).

Recommending a particular cropping system over others implies a knowledge of expectations from each. Thus the key word is prediction, the very essence of planning. Every planner predicts; probably every farmer who plants a crop bases that action on a prediction, although perhaps intuitively. Therefore our goal is not to change the system, but simply to sharpen ittogain a more quantitative prediction ability.

Two types of models require development. One, when fed all the information on the environment and management proposed for a specified crop, will simulate reality and predict the yield. The second model should be able to scan all feasible cropping alternatives, optimize each, and predict their yields, together with a package of management recommendations. Only the demands on (and therefore the mathematical procedures of) these models differ, the input requirements for both being the same. What is needed in the way of input are transferable relations quantifying genetically controlled crop responses to environment, and site-specific measurements of the latter. Details of the needed relations and measurements will be developed with reference to the figures in this paper.

Transferable Relations between Crops and Their Environment

The most broadly applicable relationship, and the most readily quantified with available data, is that between energy available for photosynthesis and other biological processes and yield of a given crop species when managed with the best technology known. Recognition of such a relation in the tropics is made by Clements (1964), who, in citing an earlier study (Clements 1940), notes: "Despite similar soils, mean temperatures, and adequate moisture, differences due mostly to the absorbed sunlight caused about double the growth of (sugar) cane in one area of Hawaii as compared with another." Such an observation, if valid, has far-reaching implications for the siting of sugar plantations and selection of crop technology.

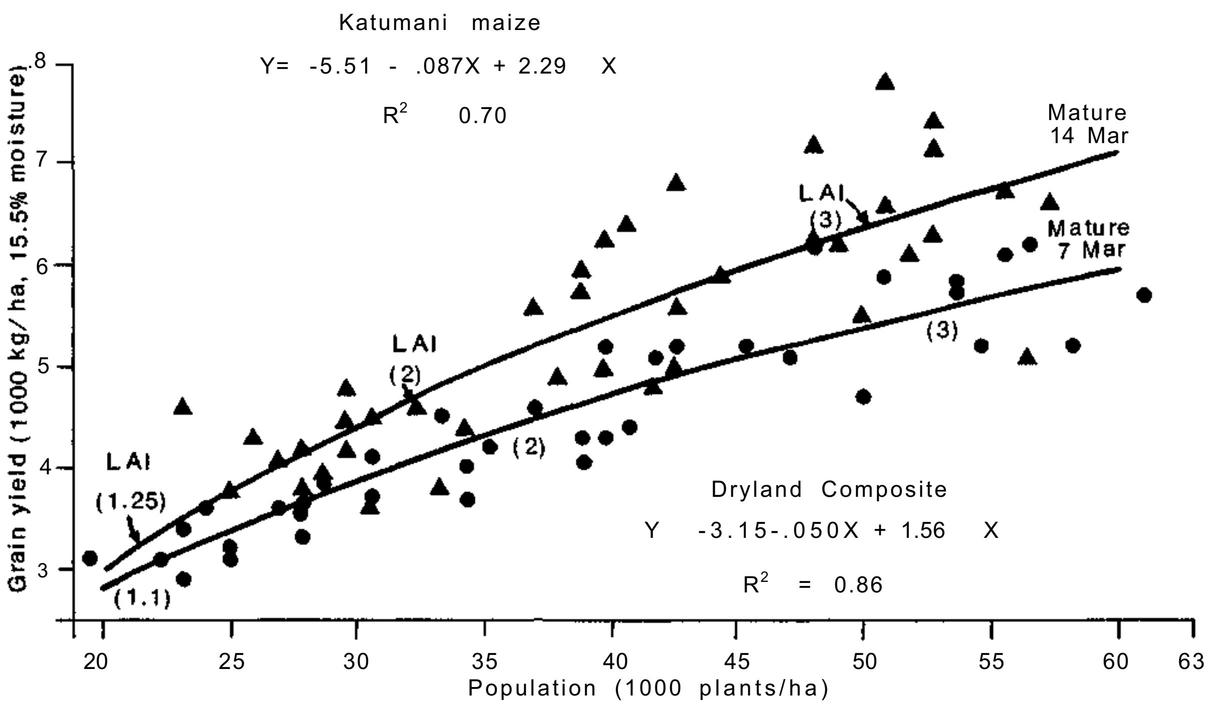

Figure 5. Maize grain yield versus plant population, at Katumani Drylands Farming Research Station, Kenya. Experiment planted 16 Nov 1977. USAIDIKARI Project: Cropping systems for marginal rainfall areas (Experimental conditions: High fertility, nearly adequate water).

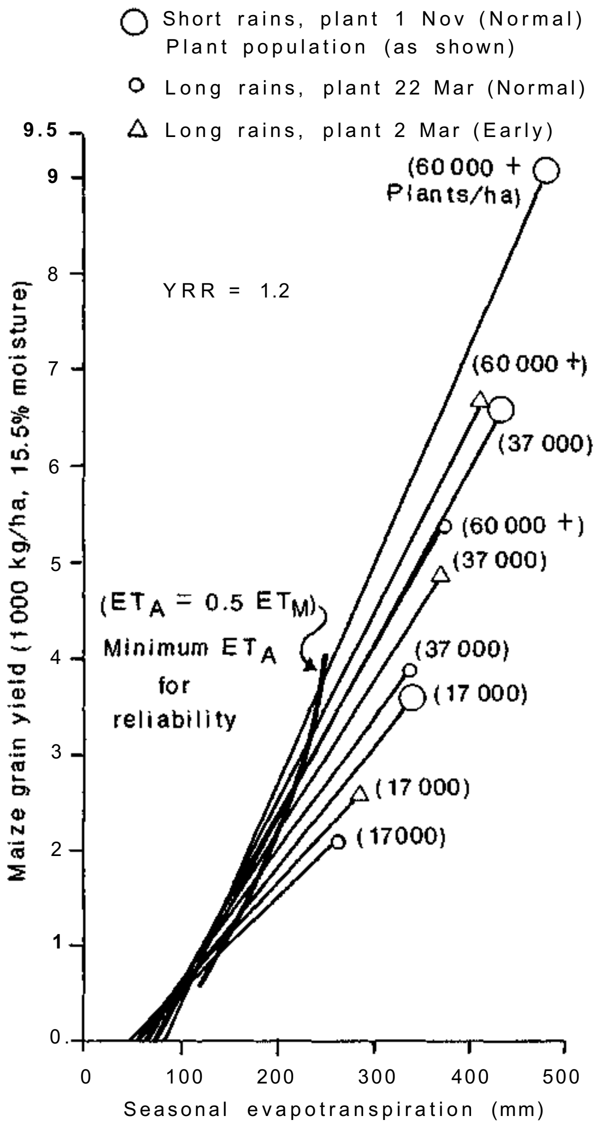

Figure 6. Suggested family of Y vs ET functions for Katumani maize planted on three dates at three plant populations. Water requirements, ETM, @ maximum yield, YM vary greatly, but the yield reduction ratio, YRR, remains constant (see text). Illustrative only. Research in progress.

Cotton is produced under rainfed conditions in the Pacific Coast Region of Nicaragua. The volcanic soils of the area are generally fertile, well-drained, fairly deep, and of moderate to high water-holding capacity. Technology of production is uniformly at a high standard. Fields are large and machine-worked, and fertilizers and insect sprays are applied routinely. Processing and marketing are controlled by government, so yields are measured and published for each district individually by the Comision Nacional del Algodon.

It is generally believed that crop yields in the Managua-Granada area are often limited by water availability, and thefeasibility of developing groundwater for irrigation of cotton and other crops was under study by a UNDP team in 1974. Acting as a consultant, I developed the findings in Figure 1, where, forthe 9-year period (1965-1973) average seed-cotton yields from 116 growers in four districts in the Managua-Granada area are plotted versus total sunshine hours during the 3 principal growing months, starting 6 weeks after planting.

For 8 of the 9 years, 79% of the annual variation in cotton yields may be explained by sunshine hours. Only in 1972 was water clearly limiting (Fig. 1). On the face of it, irrigation development would not appear warranted. However, the answer is not quite that simple.

Some of the advantages of irrigation are obvious. First, 1000 kg/ha more seed cotton should have been produced in 1972. Averaged over the 9-year period, that amounts to 111 kg/ha per year. Next, irrigation would permit planting at a later date, extending the season into the dry period, which is less cloudy, hence gaining sunshine hours and yield. The figure shows the expectations for sunshine hours and corresponding yields for plantings in mid-July (present practice), mid-August, and mid-September. Moving the planting date to August would increase yields some 400 kg/ha, and to September, another 300 kg/ha. Thefeasibility of this suggestion is already established by some fortunate growers in the Chinandega area who have extremely deep soils with high water-holding capacity. They do plant later and receive markedly higher yields.

Disregarding irrigation. Figure 1 offers guidance as to the level of crop technology that can be economically applied to a cotton crop in the area in question. For example, it would be wasteful to fertilize at levels sufficient for 4000 kg/ha, when 3000 is the upper limit of yield expected.

Figure 2 shows a high correlation between daily production of alfalfa and daily rates of evaporation, each taken as seasonal averages.

Stewart and Hagan (1969a) show that, due to cycling of photosynthates out of root reserves in the early season and into the root system in the late season, the apparent fodder production per unit of evaporation is higher in spring than indicated in Figure 2, and lower in fall. The mid-season production and the total season average are as shown.

Evaporation integrates a number of weather factors, the principal one being solar radiation. Others include temperature, humidity, and wind. The crop-water requirement is governed directly by the same factors, and for alfalfa averages approximately 0.85xClass-A pan evaporation. The average includes recovery periods after cutting. Therefore, Figure 2 provides the information required for predictive estimates of production, water use, and water-use efficiency in different climatic zones.

Another point of interest concerning the data shown in Figure 2 is that six different varieties of alfalfa are represented in the 11 years of data; each is known to be "well adapted" to the local area. This suggests defining an adapted variety as one which, when given adequate water and a high level of management, produces at the maximum level of water-use efficiency that accords with the climate.

Figure 2 implies that a full-cover stand of well-adapted and vigorously growing alfalfa does not become light saturated within the ordinary range of agricultural climates. This is not true of many crops; e.g., Stewart and Hagan (1969b) report that wheat requires twice as much water to produce a yield in Texas, where evaporative rates are high, as it needs for the same yield in Montana.

Maize, the most important food crop in Kenya and of great importance in much of the semi-arid tropics, is intermediate between alfalfa and wheat in light-saturation value, according to findings in 2 years of coordinated experiments (Stewart et al. 1977a).

In Figure 3, yields of maize grain from the eight coordinated experiments are plotted versus the average daily rate of Class-A pan evaporation during the season. Well-adapted hybrids of similar maturity (~120 days) were grown in each instance, with adequate water and the best management practices known, except where noted. All of these conditions are met in four of the eight experiments (Logan, Utah, 1975; Ft. Collins, Colo, 1974; and Davis, Calif, 1974 and 1975), which are linked by the solid line to suggest a practical upper limit to yield of medium-maturity maize varieties in climates represented by the evaporation rates shown. The line is extrapolated to lower evaporation zones, suggesting zero grain yield below approximately 2.8 mm per day.

The maximum yield reached is 12 000 kg/ha at the suggested evaporation rate of about 7.5 mm/day. Presumably this represents the situation when light saturation occurs. Yuma, Arizona is a special case, with evaporation rates averaging more than 9 mm/day and daily maximum temperatures averaging 41.2° and 36.8°C during the pollination periods in 1974 and 1975, respectively. Even the highest irrigation treatments applied failed to completely supply the water requirement.

At Fort Collins in 1975, planting was delayed until 27 May by cold wet conditions. Frost then foreshortened the grain-filling and maturation period with harvest on 19 September. Yields were below normal all over Colorado, as well as in the experiment. At Logan in 1974, phosphorus fertilizer applications were limited, with the result seen in Figure 3. Thus the figure shows both an overall climatic limitation to yield, and the additional effects of inclement weather and deficiencies of water and fertilizers. Effects of such negative yield factors will receive further attention later.

Yields from two maize experiments at Katumani, Kenya, are fitted within the framework of Figure 3. The first experiment was not irrigated, and falls below the potential yield line. The second experimentwas irrigated, hence isfitted along the (extrapolated) line. The indicated rate of Class-A pan evaporation is 5.1 mm/day, whereas that actually measured was 3.8. The ratio (3.8/5.1) gives rise to a factor of 0.75, occasioned by the fact that all evaporation pans in Kenya are screened against birds and animals. It may be noted that factoring of evaporation pans for differences such as screening, siting, etc., is an important goal of the project, not as yet accomplished. Later studies will provide the correct factor, but for purposes of illustration, 0.75 is accepted as reasonable.

Other transferable relationships between crops and their environment must be narrowed to the varietal level and translated into relative values in order to be transferred from one set of conditions to another. Examples of such relations are (a) yield per unit land area versus plant population, and (b) yield versus crop water supply or ET, i.e., Y vs ET functions. Both of these relations are discussed later, along with site-specific measurements of the environment. It will be demonstrated how the relative value relationships are returned to absolute values fitting the new circumstances.

Environmental Measurements and Fitting of Transferable Crop Relations

Thefirststepin making the general relationship expressed in Figure 3 site specific is to collect and analyze Class-A pan-evaporation records. Figures covering the past year at Katumani (30 Jul, 1977-29 Jul, 1978) are shown as daily averages for 10-day periods in Figure 4. This figure "looks ahead" at evaporation expectations during the 120-day growing season following any given maize-planting date one might consider. Based on the 120-day average evaporation rate, the potential yield of maize (derived from Fig. 3) is plotted directly above the planting date. The continuous dark line linking potential yield to planting date is developed in this manner.

Figure 4 also includes the 20-year rainfall pattern from the nearby town of Machakos, compiled by Dr. H. M. Nadar, Agronomist in the project. Rainfall does not influence potential yield, but as the curves indicate, it is the key determinant of planting date in rainfed agriculture. Farmer practice is to wait until the rains have definitely begun before preparing the seedbed and planting. In Figure 4, arrows are affixed to the potential yield line, showing normal planting dates which accord with the bimodal rainfall pattern. On these dates, a potential of 9100 kg/ha is suggested for the short-rain season, but only 5400 kg/ha in a long-rain-season.

Because of the nearly complete dryness from June through September and early October, little flexibility exists in the short-rains planting date. However, if the land is fallowed or a short-term crop like beans is grown during the short rains, and weeds are controlled in January and February, then planting could in many years be accomplished with the lighter rains around March 1. This would increase the potential yield to 6700 kg/ha, while making better use of the rains to come in two ways. First, the rains in early March would not be evaporated during land preparation and lost to the crop, and secondly, the rains would effectively cease 30 to 40 days before crop maturity, instead of the usual 50 to 60 days. In other words, the chance of realizing the higher potential created by early planting is greater than that of realizing the lower potential associated with the normal planting date.

Following the sequence described in the introduction, the next influence on potential yield that requires attention is plant population. Figure 5 plots relationships found between yield and plant population in the first experiment planted at Katumani in November, 1977. Katumani maize and another shorter-maturity composite were tested, but only the former is of interest here. Irrigation was not available, but rainfall was above normal, and although water deficits occurred, they were not severe. Therefore, a strong response is seen throughout the range of plant populations tested.

It is apparent that the optimal plant population for realizing the potential yield levels reflected in Figure 4 is in excess of 60 000 plants/ha. This agrees with many published results from plant-population studies in the USA and elsewhere, using medium-maturity maize cultivars. Also, in agreement with other studies is the finding that the optimal leaf-area index (LAI) is well above 3, indicated in Figure 5 at a population of 51 000/ha.

The current recommendation to farmers is to plant Katumani maize at a spacing of 30 cm in rows 90 cm apart, thus at 37 000 plants per ha. Few farmers actually plant this heavily, so the level of 17 000/ha has been selected for the example (Fig. 6). When yields at different populations in Figure 5 are made relative to the maximum (yield at 60 000 + plants per hectare = 100%), we find yield at 37 000 plants/ha equals 73% of maximum and 39% at 17 000 plants/ha. Assuming this relative-value relationship to be valid for Katumani maize whenever water is adequate (or nearly adequate), and other management factors are at high levels, we are now able to predict potential yields not only for different planting dates, but modified by plant population as well.

Our final interest is in quantifying responses to drought of various intensities, and we have already determined yield with no drought, i.e., yield when actual evapotranspiration, ETA, is equal to ETM, and the water requirement is satisfied. The first step is to quantitatively estimate what the water requirements are when planting maize at Katumani on different dates and different populations. Many workers have shown close relationships between crop ET rates and evaporative conditions, with changing coefficients as the crop progresses from one growth stage to another. Doorenbos and Pruitt (1977) summarize much of this work.

We favor relation of maximum ET rates to Class-A pan evaporation, thus enabling estimation of seasonal ETM and maximum yield YM from the same set of (pan) readings. If only a total figure for seasonal ETM is desired, a quick estimate can be made for medium-maturity maize by summing Class-A pan evaporation expected in theseason, and multiplying by 0.65. This assumes a full leaf canopy, i.e., LAI equal to or greater than 3.0. When plant population is reduced to 37 000/ha, LAI = 2.2, and the water requirement will be reduced approximately 10%. At 17 000 plants/ha, LAI = 1.0 and the reduction in water requirement is approximately 30%. These relationships have been used to estimate values of ETM corresponding to the values of potential yield YM in Figure 6.

The final transferable relationship governed by crop genetics is the relative value Y vs ET function. This function has been demonstrated to be linear in form for a number of crops, including maize (Stewart et al. 1975), pinto beans (Stewart et al. 1976), pink beans and cotton (Stewart et al. 1977), and light red kidney beans and the new UC-82 A square-round processing tomato (unpublished).

Stewart et al. (1975) have defined the "Yield-reduction ratio," or YRR, as the relative value slope of the Y vs ET function. It is percent reduction in yield, divided by the percent evapotranspiration deficit, ETD. ETD in turn is defined as ETM-ETA. Therefore, %ETp= ETD/ETMX100. Stewart et al. (1977a) show that YRR is a varietal characteristic in maize, and reproduces itself in different environments even though ETM and YM may be quite changed.

In Figure6, a valueof 1.2 has been assigned to represent YRR of Katumani maize, and all nine Y vs ET functions are drawn accordingly. As with other portions of this illustration, a definitive determination of YRR for Katumani maize has not yet been made, but the value of 1.2 is reasonable and suits the present purpose.

The completed figure comparises a family of Y vs ET functions useful for making decisions about optimal dates of planting and plant populations, based on anticipated crop-water supply, i.e., on ETAexpected to resultfrom available soil water in storage at planting time, plus effective rainfall during the growing season. Having selected the practices to follow, the appropriate Y vs ET function provides an estimate of expected yield, again according to anticipated ETA,

One note of caution is indicated in Figure 6 by the curved line cutting through all 9functions at approximately the points where ETA = 0.5 ETM. This is to indicate that the functional relation cannot be relied upon after ETD exceeds 50% of ETM. With such severe deficits, especially if grouped in certain growth stages rather than being spread throughout the season, growth may become quite abnormal, and grain yield may plunge to little or nothing. Therefore, for example, Figure 6 indicates that the nine planting options are viable if the water supply guarantees an ETA of 250 mm or greater, but only the lower five options are open if expected ETA is 200 mm, and only the lowest two options if expected ETA is 150 mm.

Symbols and Definitions

Adapted variety

Any crop variety which, when given adequate water and a high level of management, will produce at the maximum level of water-use efficiency which accords with the climate.

LAI

Leaf-Area Index; the area of leaf surface (one side only) per unit land area.

YM

Maximum yield is the expectation when water is adequate, limited only by available energy and plant population. The starting points for Y vs ET functions, as plotted in Figure 6.

ETM

Maximum evapotranspiration is that which occurs when the crop-water requirement is fully satisfied. YM is the corresponding yield expectation.

ETA

Actual evapotranspiration, which may equal ETM if water is adequate, or may be at any lesser level if water is limited.

ETD

Evapotranspiration deficit, or ETM-ETA. To express intensity, may be given as a percentage of ETM.

Eo

Evaporation from an extensive free water surface (after Penman).

Water-Production Function

Any functional relation between crop yield and water.

Yvs ET

A water-production function showing crop yield versus seasonal total evapotranspiration over the range from ET_M downward. This single-valued function does not specifically consider the linkage of ET deficits with particular growth stages, hence it represents the highest yield expectation at any given seasonal ETD level, i.e., it assumes optimal timing of ET deficits.

YRR

Yield Reduction Ratio; the relative value slope of the Y vs ET function as it declines from ETM, YM. Percent reduction in yield per percent ETD YRR for a given crop and variety is thought to be a genetic characteristic, reproducible in different environments. It is also a measure of drought resistance — the lower its YRR, the more drought resistant the variety.

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Plant and Atmospheric Parameters in Water Stress Studies

M. V. K. Sivakumar and S. M. Virmani*

Summary

In order to improve water-use efficiency in productive agriculture, an understanding of the crop-water deficits and the controlling parameters is essential. Plant-water deficit that develops in any particular situation is the result of a complex combination of soil, plant, and atmospheric factors, all of which interact to control the rate of water absorption and water loss.

Some of the important atmospheric and plant parameters that could be effectively used in quantifying water stress effects have been examined here. Net radiation, air temperature, vapor-pressure deficit, and wind speed are the atmospheric parameters that help in the description of canopy microclimate and the local potential for water loss at different points inside the plant canopy. The action of and the interaction among these parameters, depending on soil moisture conditions, produce crop-water deficits and such deficits could be quantified, using plant parameters such as stomatal resistance, leaf-water potential, leaf area, and leaf temperature.

It is essential to note that a feedback mechanism exists in the soil-plant-atmosphere continuum and hence the parameters described here should be examined from the holistic aspect and not in isolation. Such an examination should aid in understanding of the canopy-moisture environment.

Semi-arid tropical areas are usually characterized by low to very low precipitation with a marked seasonal variability. Water is the limiting factor for agricultural productivity, and field crops suffer — at times severely — from water deficits in these areas.

Any solution to climatological water deficits in a given area must be evolved by the development of effective crops and techniques for soil and water management. Evaluation of crop-water stress is an important prerequisite in such studies. Effective evaluation of crop-water stress should consider the plant response to environmental conditions and characterization of these conditions.

Review of the extensive literature on evaluation of crop-water stress is beyond the scope of this paper. The purpose here is to discuss semiquantitatively the importance of various plant and atmospheric parameters that may be useful in water-stress experiments, drawing upon only a few data to illustrate the points.

Water Transfer in the Soil-Plant-Atmosphere Continuum (SPAC)

In evaluating the relationship between moisture stress and plant response, it is necessary to consider how water deficits develop. A simple pathway of water transfer in the SPAC (Perrier 1973) is presented in Figure 1. Water moves in response to a potential gradient. The rate of absorption of water from the soil is controlled by the efficiency of root systems, soil temperature, concentration of soil solution, and free-energy status of soil moisture.

When plant roots *are* in equilibrium with soil water and when soil moisture is at field capacity, a base level of leaf-water status can be defined (Slatyer 1963). Assuming a low or near-zero evaporative demand situation (as happens during the night), losses of water are

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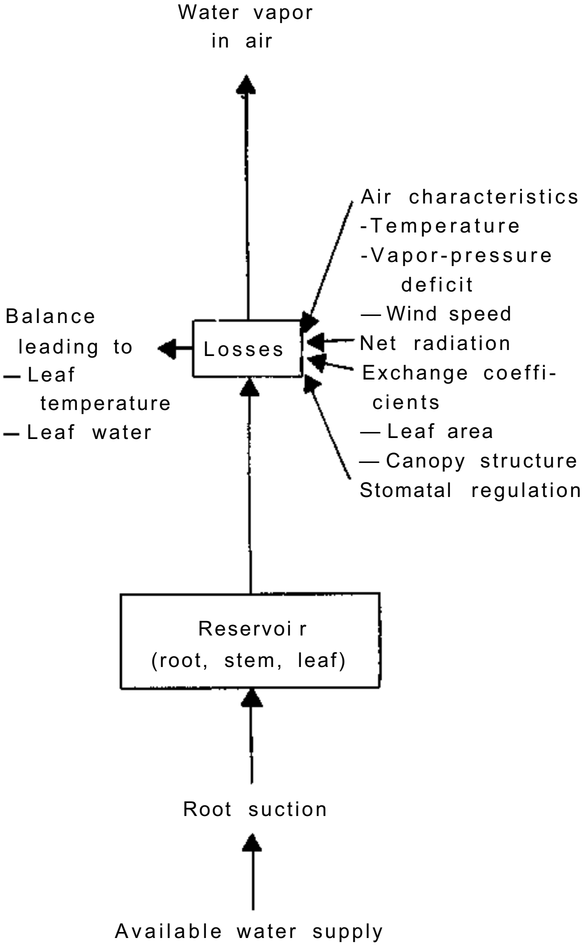

Figure 1. Water transfer in the soil-plant-atmosphere continuum (after Perrier 1973).

minimal and leaf-water status will be near the level of equilibrium with the soil water. But under field conditions, several components (such as temperature, vapor-pressure deficit, wind speed, etc.) cause a decrease in the turgor pressure of upper leaves in the crop canopy and an increase in the rate of transpiration. Transpiration is also controlled by leaf area and structure and extent of stomatal opening. Transpiration and the factors driving this dynamic process have an important influence on leaf temperatures.

Assuming a near-complete crop cover, moisture stress is the result of an imbalance between the supply furnished by soil water and the amount needed by the plant as influenced by the atmosphere.

The pathway of water transfer (Fig. 1) suggests several important atmospheric and plant parameters useful in water-stress studies. The discussion presented below is intended primarily to evoke interest in these important measurements in order to quantify water-stress effects under field conditions.

Atmospheric Parameters

The process of transpiration may be physically described in terms of a resistance to a diffusive and turbulent vapor flux in the external air and a similar diffusive resistance that is the resultant of internal leaf geometry, including the stomata and (parallel to the latter) a resistance to the vapor diffusion through the cuticle (Raschke 1956). According to the theory of turbulence, the upward flow of water vapor in air is equal to the product of the vertical gradient of vapor pressure and the rate of mixing as determined by wind speed. The important atmospheric parameters that control the rate of transpiration appear to be air temperature, wind, vapor-pressure deficit, and the energy (net radiation) available to the canopy.

Air Temperature

The response of individual plant physiological processes to changes in temperature are not well known because of the interaction among processes and other environmental factors. Temperature response varies from crop to crop and also from variety to variety within a plant species.

Temperatures in the hot arid and semi-arid climates are the highest in the world (Critchfield 1966). The generally clear skies facilitate maximum radiation in daytime and rapid loss of heat at night, causing wide diurnal ranges of temperature, which in summer may reach 20 to 30°C in hot areas. The photosynthetic process appears to become heat-inactivated at excessively high temperatures while respiration is not inhibited; the apparent photosynthesis declines rapidly under these conditions (Moss et al. 1961).

The harmful effects of excessive temperatures are usually aggravated by lack of available moisture. Hot dry winds will further increase the damage. The yield of grain sorghum is adversely affected by high temperatures occurring at flowering (Skerman 1956). The reduction in grain set was found to be due to high temperatures. Atmospheric temperature affects transpiration through its influence on leaf temperature and hence on leaf-water-vapor pressure (Kramer 1969).

Stegman et al. (1976) showed that the changes in the xylem sap pressure (leaf-water potential, as measured with a pressure bomb) to the available soil moisture are dependent on air temperatures (Fig. 2). At any given available soil-moisture level, an increase in the air temperature from 15.6 to 37.8°C resulted in a decreased leaf-water status as reflected by increased xylem sap pressures. Using the regression relationships of leaf-xylem pressureversus ambient air temperature and available soil-moisture level, allowable root-zone moisture depletion limits (expressed in % as 100 minus available moisture) were computed (Table 1). Wide ranges in allowable depletion limits are shown for each crop. The maize model, for example, predicts that at 37.8°C ambient air temperature no soil moisture could be allowed to be depleted below 100%. At 26.7°C, 40% soil moisture could be depleted; at 15.6°C, the xylem sap pressure is not likely to attain the estimated critical level until the available soil moisture is depleted to 8%.

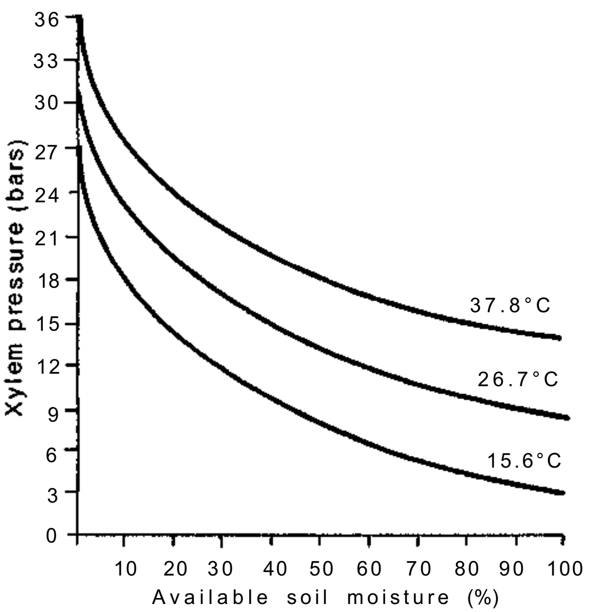

Figure 2. Correlation between xylem pressure of sugarbeet leaves and soil moisture at three ambient air temperatures (after Stegman et al. 1976).

Vapor Pressure Deficit

The influence of air humidity on growth of plants has often been underestimated (Went 1957). Even with sufficient water supply, low air humidity is one of the causes of daily water deficit and it is possible that they may have a permanent and irreversible influence on the structure of leaf surfaces which in turn may influence the internal factors affecting transpiration (Slavik 1970).

The vapor pressure of the bulk air is the actual vapor pressure of the air which is a direct indicator of the moisture content of the air. As air temperature changes, the relative humidity changes, even though the actual moisture content of the air remains the same. Relative humidity therefore is meaningless in itself when considering transpiration. Vapor-pressure deficit (VPD) — often used as an indicator of atmospheric-moisture content — is likewise not of much value in itself unless the leaf and airtemperaturesare identical. If theleaf temperature increases, the vapor pressure inside the leaf also changes and this increases the vapor-pressure gradient from leaf to air. The increase in transpiration from morning to midafternoon is due to this increase in leaf-air vapor-pressure deficit.

Jarvis (1976) described the functional relationship between stomatal conductance and leaf-water potentials at a given leaf-air vapor-pressure difference (Fig. 3). It is apparent that stomatal conductance rates are usually higher at low vapor-pressure deficits. An increase in the vapor-pressure difference at a given leaf-water potential reduces stomatal conductance.

From the data of controlled cabinet experiments with *Trifolium repens,* Lawlor and Lake (1976) showed that 23% of the observed variance in stomatal conductance could be attributed to changes in leaf-water potential and 36% of the variance could be attributed to leaf-air vapor-pressure difference. They have concluded that leaf-air vapor-pressure difference was at least as important as leaf-water potential in controlling stomatal conductance. Work on detached leaves of maize (Raschke 1970), and whole plants of maize (Schulze et al.

1972) showed the effects of ambient water-vapor concentration on stomatal conductance. Idle (1977) showed that higher values of water-vapor density deficit caused lower conductance.

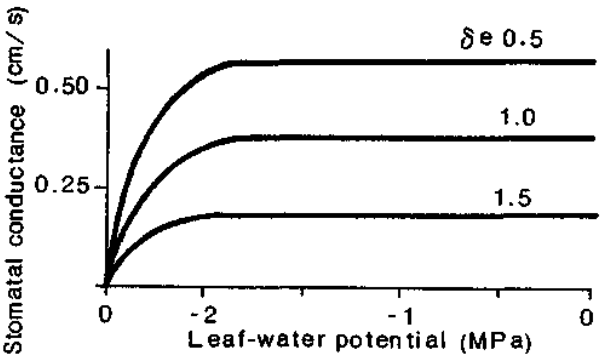

Figure 3. Relation between stomatal conductance and leaf-water potential at three levels of vapor pressure difference (de) (after Jarvis 1976).

Raschke(1976) points out that even at higher relative water content of leaves, dry air may cause the epidermis to lose water more rapidly than it can be replaced from within the leaf — which he believes would result in a narrower stomatal aperture than would be the case in moist air.

The ability of the leaves to cool by evaporative mechanisms would be restricted when relative humidity is high or when vapor-pressure deficit is low, because the air surrounding the leaf would tend to be more saturated with water vapor than on days with low humidities or high VPD. Thus, thermal stress could be imposed on the leaves.

Wind Speed

Of the atmospheric parameters, wind is the most complex in its effect on transpiration and is generally least understood. Theoretical and leaf-model work by Monteith (1965) and Gates

Table 1. Regression estimates of allowable root-zone soil moisture depletion.

Crop	Estimated critical leaf xylem pressure (bars)	Estimated allowable depletions limits at each temperature level[a] — Ambient air temperature °C: 37.8	32.2	26.7	21.1	15.6
		Carrington site-Heimdal loam — Percent				
Sugar beets	-12	0	0	42	81	97
Com	-12	0	36	65	85	95
Potatoes	-10	0	0	44	77	94
Pinto	-11.5	0	23	69	91	99
	Average	0	15	55	84	96
		Oakes site- Maddock sandy loam — Percent				
Sugar beets	-12	0	17	43	63	78
Corn	-12	0	29	60	80	92
Potatoes	-10	0	0	44	89	99
Soybeans	-12	0	29	56	75	87
Alfalfa	-14	0	25	64	86	97
	Average	0	20	53	79	91

a. Root zone depletions at which leaf xylem pressure is likely to exceed the estimated critical xylem pressure. A depletion limit of 10% means the remaining available moisture percentage is 90.

(1968) showed that an increase in wind speed may increase or decrease transpiration or have no effect, depending on the temperature and vapor-pressure differentials between leaf and air, concomitant changes in leaf-boundary-layer resistance, and variations in internal leaf resistance.

If the saturation deficit of the air exceeds that at the surface of the leaf, transpiration rate will increase with wind speed; transpiration rate will be independent of wind speed when the deficit is same; and transpiration will decrease with increasing wind speed if the deficit at the leaf surface is greater than in the air (Monteith 1965).

Gates (1968) has pointed out the close link betweentranspirationand leaf temperature, the latter adjusting the balance of the energy budget. If the air is warmer than the leaf because the radiant energy absorbed by the leaf is low, an increase in wind speed will increase leaf temperature by forced convection. Hence the water-vapor pressure or concentration at saturation within the leaf will also increase, thereby increasing the driving force for transpiration. It can be expected therefore, that increased water use with increase in wind speed will be most apparent under cloudy skies, high temperatures, and low humidity.

If the leaf is warmer than the surrounding air because of considerable absorption of radiant energy, an increase in wind speed will cool the leaf by convection. Water-vapor pressure will then decline in the leaf, reducing the leaf-air vapor-pressure difference. If this reduction is greater relative to the reduction in total resistance caused by the reduced external resistance, transpiration rate and hence water use will decrease with increasing wind speed.

Obviously, as Monteith and Gates have shown, there will be times when wind causes a change of boundary resistance which is balanced by a change of vapor pressure within the leaf, resulting in change of wind speed having relatively little effect on transpirational rate.

Lomas and Lewin (1977) illustrated the hypothetical response of wheat, millet, and cotton to stomatal closure when submitted to two rates of wind speed. The ratio of mesophyll resistance (r_m) to boundary layer resistance (r_e) must be greater than 2 to obtain improved water-use efficiency from stomatal closure (at an air temperature of about 26°C). The results are presented in Table 2.

The values of r_m are taken from the literature (Slatyer 1970) and the values for r_a computed from the numerical relation ra = 3.4 V(b/u), where b is the leaf width (cm) and u is the wind speed (cm/sec).

It can be observed that while wheat will benefit under all conditions from stomatal closure — reducing its transpiration to a marked degree without affecting its assimilation — this will happen in millet and cotton at relatively high wind speeds only. At low wind speeds the assimilation rate in both crops will be reduced by stomatal closure at least as much as by transpiration.

Net Radiation

Net radiation is of basic importance in describing the physical environment of the crop since it represents, among other things, the energy available for growth. Knowledge of the spatial distribution of net radiation in a crop canopy can provide us with information about the possible magnitudes of evaporation, transpiration, and photosynthesis as well as information about the regions within the crop canopy which are most active in these processes (Denmead et al. 1962).

In the absence of advected energy, potential evapotranspiration is determined by net radiation. Measurements of the energy budget at several locations indicated that in the tropics and in the middle latitudes, 80 to 90% of the net radiation is consumed in evapotranspiration. The lower values of 80 to 85% are probably correct, because a small amount of advected energy exists, even in humid climate (Chang 1968).

Table 2. Effect of the relative magnitude of aerodynamic and mesophyll resistances on the water-use efficiency.

Crop	r_m (sec/cm)	(U = 10 cm/sec)	(U=100 cm/sec)	r_m/r_{a1}	r_m/r_{a2}
Wheat	3.0	1.08	0.34	2.78	8.82
Millet	0.9	1.08	0.34	0.82	2.65
Cotton	2.6	3.40	1.08	0.77	2.41

Under conditions of high water availability a close correlation between net radiation and evapotranspiration (ET) was noted. Tanner (1957) showed that lysimeter-determined ET was highly correlated with net radiation over an alfalfa-brome hay field and over maize in Wisconsin. Decker (1962), however, suggested that net radiation is partitioned preferentially to latent heat more than to sensible heat. Only where this is true can net radiation be used to estimate ET.

Pruitt in California (1960) has shown that net radiation and evaporative flux are generally close, but ET consistently exceeds net radiation during late afternoon, apparently due to convective heat transfer from air to evaporative surfaces. Pruitt (1964) also reports that net radiation and ET are in generally good agreement on a yearly basis at Davis, but that conditions of advection and low relative humidity cause ET to greatly exceed net radiation over short periods.

In the presence of advected energy, the potential maximum ET may well exceed net radiation. Grable et al. (1966) reported a maximum ratio of ET and net radiation of 1.31 at Gunnison, Colorado. It appears, therefore, that ET cannot be approximated from net radiation alone in arid regions. Instrumentation to measure sensible heat flux might help detect advective energy into a crop canopy and explain the observed variations in net radiation and ET. The energy balance of a surface can be determined from the relation:

$$Rn - S = LE + A \qquad (1)$$

where

Rn is the net radiation,
S is the soil heat flux,
LE is the latent heat flux, and
A is the sensible heat flux.

If LE > (Rn-S), sensible heat (A) has been drawn from the air and consumed in evaporation. This effect (consumption rather than generation of sensible heat) has often been considered prima-facie evidence of advection (Rosenberg et al. 1968).

In the investigations of water-loss factor, measurements of net radiation were widely used. Yao and Shaw (1964) have shown that differential maize spacing results in net radiation differences which are in part reflected in water use from plots. Working with different row spacings of corn plants, Aubertin and Peters (1961) suggested that knowledge of total net radiation and the area planted in the crop should enable estimation of total water requirement of the crop.

Sivakumar et al. (1978) reported that the difference in the transpiration rates between nonirrigated and irrigated sorghum could be explained by the integrated values of net radiation. Diurnal pattern of net radiation for the two treatments is shown in Figure 4. Integrated over the day, the net radiation in irrigated sorghum could account for more than 0.5 mm of higher transpiration over the nonirrigated sorghum.

Plant Parameters

The status of water in plants represents an integration of atmospheric demand, soil-water potential, rooting density and distribution, and other plant characteristics (Kramer 1969). Therefore, to obtain a true measure of plant-water deficit, the measurement should be made on the plant. Important plant parameters that could be used to characterize water stress appear to be stomatal resistance, leaf-water potential, leaf area, and leaf temperature.

Stomatal Resistance

Intensive studies (Troughton 1969; Boyer 1970b; Slatyer 1970) have provided evidence that observed reduction in net photosynthesis with increasing stress can be completely attributed to stomatal closure until severe stress exists. The similarity of the effect of water stress onthe rates of transpiration and photosynthesis (Brix 1962) and the close relationship between oscillations of photosynthesis and transpiration (Troughton 1969) both point to a dominant stomatal control on transpiration. The effect of depletion and replenishment of soil water on transpiration, as regulated bytheleaf stomates, is of specific importance to water use and its efficiency in crop production. By forcing air through the leaf at constant rate to overcome the effects of change in stomatal resistance accompanying changes in leaf-water deficit, Mederski et al. (1975) concluded that inhibition of net CO_2 assimilation with increasing leaf-

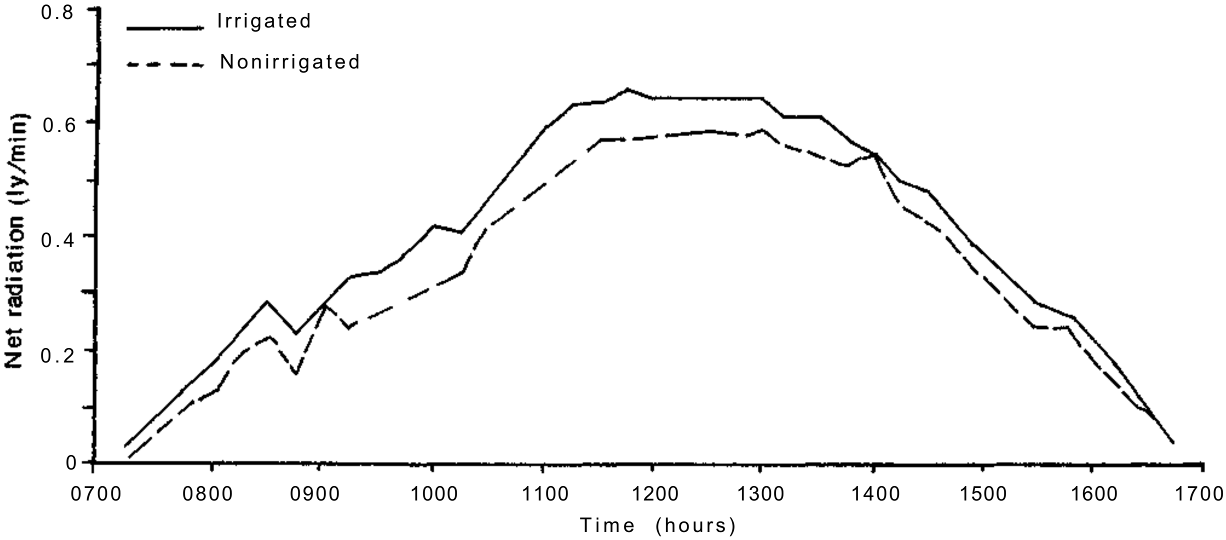

Figure 4. Diurnal variation over an irrigated and nonirrigated sorghum canopy on 20 Dec 1977 (after Sivakumar et al. 1978).

water deficit is a consequence of an increase in diffusive resistance to gas exchange.

Sivakumar and Shaw (1978a) showed that stomatal conductance (reciprocal of stomatal resistance) showed a linear response to changes in soil-water potential. When evaporation from the soil is negligible, the transpirational resistance of a crop may be close to the compound parallel resistance of all the leaves in the canopy. When the mean leaf resistance and the leaf-area index in each canopy layer are known, mean canopy transpiration resistance can be calculated.

The relationship between canopy transpirational resistance and soil-water potential for soybeans described by Sivakumar (1977) is plotted in Figure 5. Soybean canopy offers considerable resistance to transpiration as the soil-water potential approaches - 10 bars. This is probably related to visible wilting associated with high moisture stress in the field.

Sivakumar and Shaw (1978b) showed from the diurnal pattern of stomatal conductance in the canopy that stomatal conductance was influenced by the time of the day and by canopy depth. Under conditions of adequate water supply, the stomata opened early in the morning and remained open until about 1600 hours. With decreasing irradiance thereafter, the stomatal conductance showed a rapid drop. Under water-deficit conditions, stomata were open only for a short period of 2 hours in the morning, partially open until 1400 hours, and then closed completely thereafter. It appears that when the soil is dry, leaf conductances drop considerably to restrict transpiration.

An extended drying cycle decreases the stomatal conductance of water vapor and of CO_2. With the decreasing supply of CO_2 to photosynthetic sites, it is reasonable to expect a decrease in photosynthetic activity to reduce

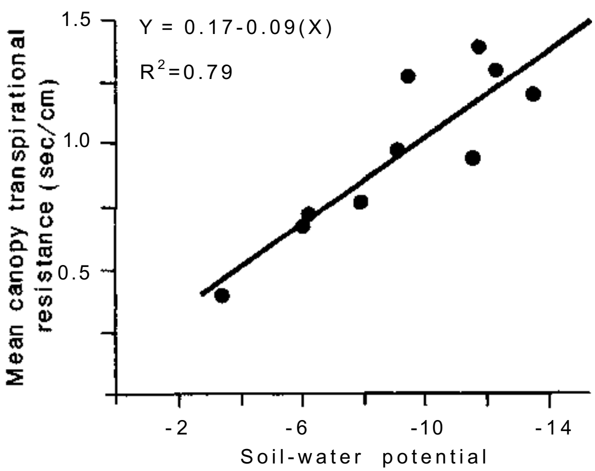

Figure 5. Mean canopy transpirational resistance as a function of soil-water potential during the growing season (after Sivakumar 1977).

the rate of dry-matter accumulation. Sivakumar and Shaw (1978a) showed that relative growth rate of soybeans was closely related to stomatal conductance. The indirect effect of loss of turgidity on the regulation of stomatal conductance and hence on net photosynthesis is evidenced by the reduced growth rates. Maintenance of higher stomatal conductance should be possible through effective water-management practices, leading to higher growth rates.

It appears therefore that stomatal conductance could be used as an effective indicator of water stress because of its close relationship with soil-water potential and growth rates.

Leaf-Water Potential

The water potential of planttissue has become a standard means of expressing plant-water response. For example, Johnson et al. (1974) reported that the rates of net photosynthesis and transpiration of ring leaves and ears decreased linearly with decreasing leaf-water potential. Brady et al. (1974) reported that estimation of plant-water potential is a possible aid in irrigation scheduling.

According to Slatyer (1969), the level of plant-water potential and hence of internal water deficit is influenced by two main factors:

1. level of soil-water potential, and
2. diurnal lag of absorption behind transpiration.

In turn, each of these is influenced by other factors, both environmental and physiological.

The response of leaf-water potential to changes in soil-water potential are plotted in Figure 6 (Sivakumar and Shaw 1978a). When soil-water potential decreased, leaf-water potential also decreased. The relative scatter of leaf-water potential at any given soil-water potential is at least partially due to the different atmospheric evaporative demand conditions prevailing during the observational days.

Boyer (1970a) showed that as leaf-water potentials decreased, leaf enlargement was inhibited earlier and more severely than photosynthesis or respiration. This fact suggests that minimal leaf turgor must be present before rapid leaf enlargement will occur. Growth was completely halted by a drop of leaf-water potentials to about -4 bars in sunflower (Boyer 1970a), -7 bars in maize (Acevedo et al. 1971), and -12 bars in soybean (Boyer 1970a).

Leaf-enlargement rate as a function of leaf-water potential is plotted in Figure7 (Sivakumar and Shaw 1978c). It appears that leaf enlargement is closely related to leaf-water potential. A

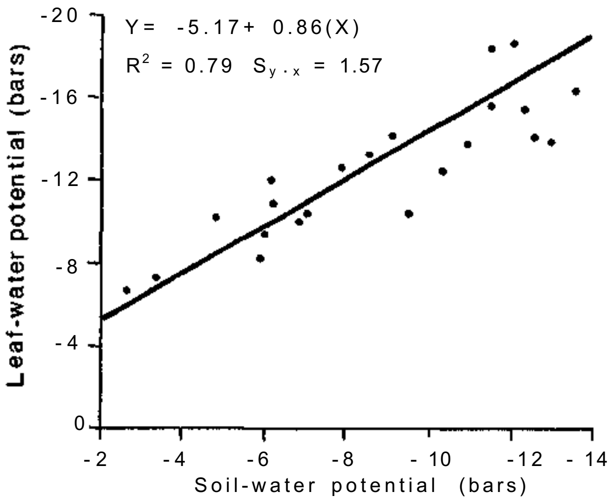

Figure 6. Response of leaf-water potential to changes in soil water potential (after Sivakumar and Shaw 1978a).

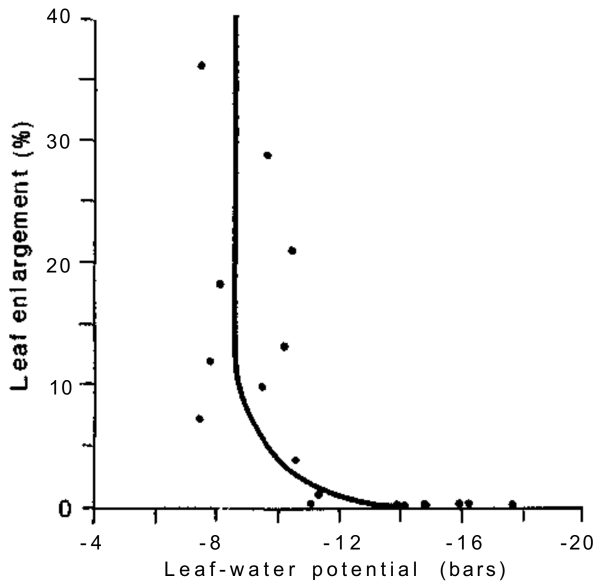

Figure 7. Leaf-enlargement rates for soybeans as a function of leaf-water potential (after Sivakumar and Shaw 1978c).

major decrease in leaf enlargement occurred near -8 bars, and at a leaf-water potential of -12 bars the growth was completely halted. In a constant-environment chamber, Boyer (1970a) found that enlargement was 25% of the observed maximum at -4 bars; at -12 bars, the leaf enlargement dropped to zero. Soybean plants under field conditions are more adapted to moisture stress and this appears to be the reason why 25% of the observed maximum enlargement occurred at -8 bars leaf-water potential as against -4 bars reported by Boyer (1970a).

In greenhouse studies, Jordan (1970) observed that although potentials determined by pressure-chamber technique represent only instantaneous values, these values can be correlated with growth response. The relation between leaf-water potential and relative growth rates of soybeans presented by Sivakumar and Shaw (1978a) is plotted in Figure 8. There is a considerable scatter around the regression line but the trend shows that relative growth rates increase as leaf-water potentials increase. Observed reduction in growth rates with low leaf-water potentials could have been brought about by increased respiration rates associated with increased plant temperatures and reduced photosynthetic rates resulting from reduced CO_2 intake.

Stegman and Bauer (1977) showed that relative root-dry matter yield accumulation from emergence to each sampling datein sugarbeets was related to the corresponding average

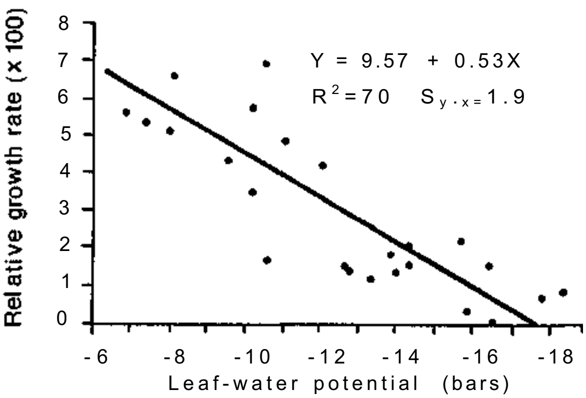

Figure 8. Relative growth rate of soybeans as a function of leaf-water potential (after Sivakumar and Shaw 1978a).

leaf-water potential from emergence to sampling date. A maximum relative yield of 1.0 in their investigations corresponded to an average seasonal leaf-water potential of -11 bars. When the seasonal leaf-water potential averaged -15.0 bars, relative yield was reduced to 0.6. At -21.0 bars, the relativeyield was only 0.1 that of the yield associated with the -11 bar seasonal average.

Leaf Area

Shawcroft et al. (1970) suggested that leaf-area could be used as a plant parameter to evaluate water status of a crop under field conditions. Very little research has been done in this area because of the tedious work involved in measuring leaf-area. Recent developments in leaf-area integrators, however, have eased the task of measuring leaf-area. If leaf-area meters are not available, one can use simple empirical equations (Sivakumar 1978) to predict leaf-area.

Sivakumar and Shaw (1978c) showed that leaf-area distributions may be used to describe water-stress effects on canopy developments. For example, leaf-area distribution with canopy height for stressed and nonstressed soybeans is presented in Table 3. Analysis of variance showed that there were significant differences in leaf-area index between the treatment for all canopy layers except the 15- to 30-cm layer. Nonstressed soybean plants showed a larger leaf-area index in the top layers than did the stressed plants. Soybeans under moisture stress showed higher leaf senescence, and hence lower area index values, in the lowest canopy layers.

Using the change in average leaf-area (leaf-area/number of leaves) per plant over a period of 7 days, Sivakumar and Shaw (1978a) developed an index termed "rate of leaf-area expansion." Rate of leaf-area expansion showed that at low soil-water potentials, the leaves show very little expansion (Fig. 9). In fact the rate of expansion shows negative values because of the onset of senescence brought about by higher water deficits. Gandar and Tanner (1970) observed that, over the growing season, diminished leaf enlargement caused by short periods of water deficits could result in a substantial reduction in total leaf growth.

Because leaf-area is an important factor in carbon assimilation, it follows that changes in

Table 3. Leaf-area index (leaf area/unit land area) in different strata of the crop canopy for stressed and nonstressed soybeans. Each observation is the mean of 40 plants.

Days after planting	Canopy depth (cm) from the top											
	Stressed soybeans						Nonstressed soybeans					
	0-15	15-30	30-45	45-60	60-75	Total	0-15	15-30	30-45	45-60	60-75	Total
71	2.1	1.0	0.4	0.2	-	3.7	2.2	1.1	0.7	0.5	-	4.5
78	1.9	1.2	0.7	0.2	-	4.0	2.4	1.2	0.9	0.6	0.3	5.4
85	1.5	1.2	0.8	0.4	0.1	4.0	2.3	1.2	1.2	0.9	0.5	6.1
92	1.5	1.2	1.1	0.5	0.1	4.4	2.1	1.5	1.2	1.1	0.6	6.5
99	1.4	1.0	0.8	0.5	0.2	3.9	1.7	1.4	1.2	1.0	0.5	5.8
106	1.3	0.9	0.6	0.2	-	3.0	1.7	1.2	1.1	0.7	0.4	5.1
111	1.1	0.8	0.6	0.2	0.2	2.9	1.4	1.0	0.8	0.5	0.4	4.1

leaf-area are related to changes in growth rates. Relative growth rates of soybeans were related to the index, rate of leaf-area expansion. The decrease in growth rates with the rate of leaf-area expansion was linear. Sivakumar and Shaw (1978a) observed that since the rate of leaf-area expansion showed as good a correlation with soil-water potential and growth rates as leaf-water potential and stomatal conductance, it appears to be one of the potential plant parameters which could be used to quantify water-deficit effects.

Leaf Temperature

Plant-leaf temperatures are controlled by radiational, convectional, and transpirational energy-exchange processes. When the disparity between transpiration and absorption of water increases, leaf-water deficits develop. Subsequently stomata close, transpiration decreases, and leaf temperatures rise. It was shown that transpiration reduces leaf temperature considerably (Gates 1968; van Bavel and Ehler 1968). Miller et al. (1971) reported that leaf temperature and relative water content were highly correlated, stating that difference in temperatures of leaves similarly exposed is a sensitive indicator of plant-water stress. Myers (1970) also suggested that crop temperatures may be used as an estimate of moisture stress.

The environmental stress imposed on a leaf could be better explained by considering the difference between leaf temperature and air temperature — the leaf-air temperature differential. Ehler and van Bavel (1967) showed that this differential is strongiy related to soil-water availability (Fig. 10). Six days following irrigation, on 20 July, leaf temperatures were considerably below airtemperaturesthroughout most of the 24-hour period. But on 13 July, just before irrigation, leaf temperatures in the dry soil remained above air temperature essentially from dawn to dusk; in late afternoon, they rose to as much as 5 degrees C above air temperature. This effect was explained to be a direct consequence of the diminished rate of transpiration due to the significant stomatal closure.

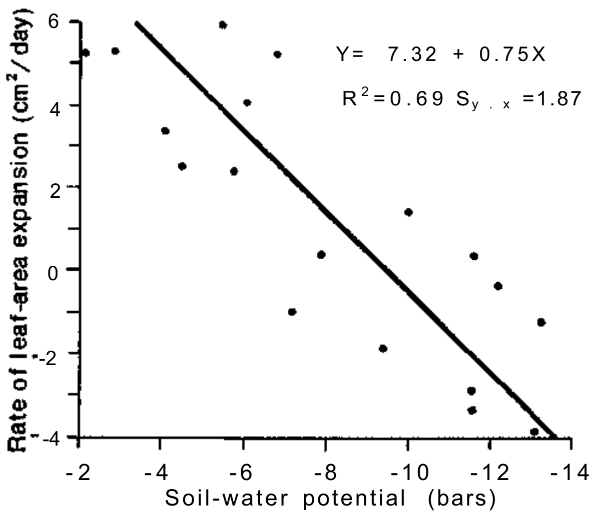

Figure 9. Rate of leaf-area expansion of soybeans as a function of soil-water potential (after Sivakumar and Shaw 1978a).

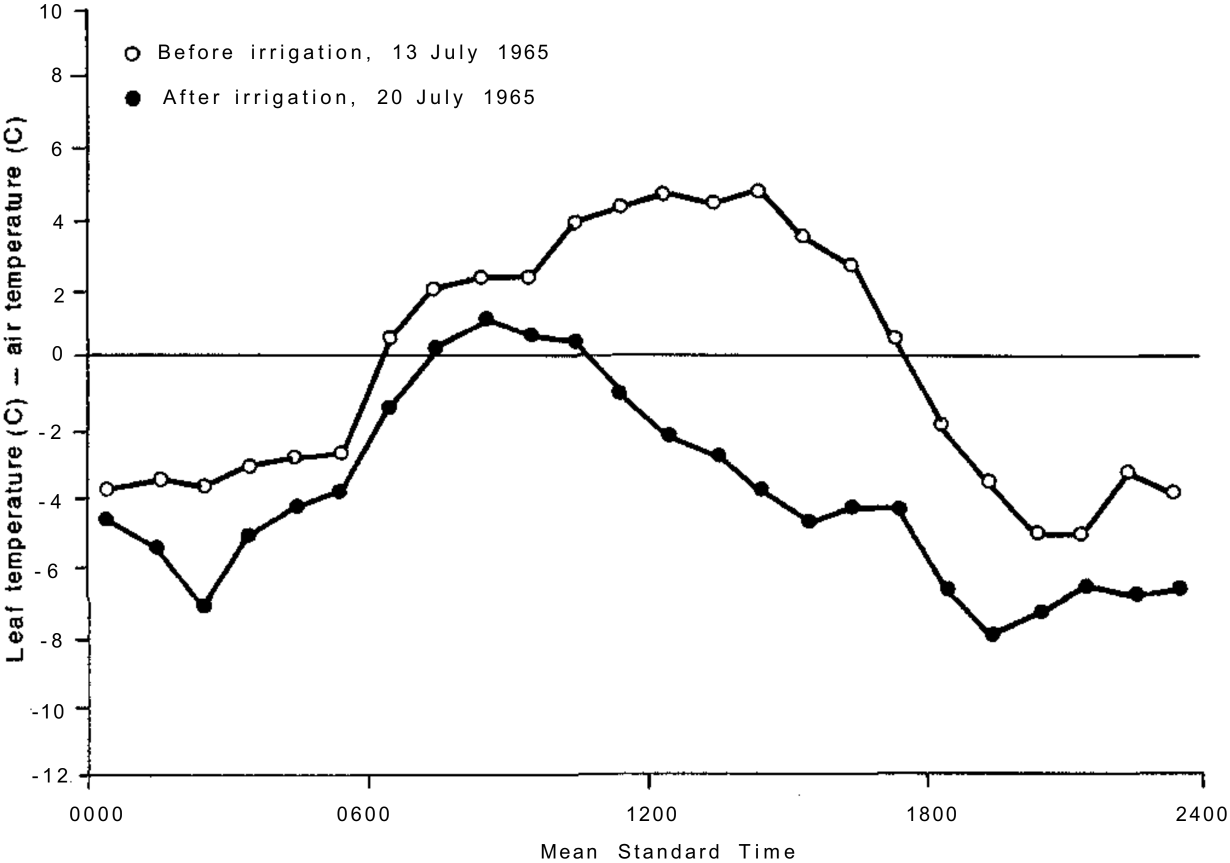

Figure 10. Hourly average of leaf temperature minus air temperature (2m above the canopy) before irrigation on 13 July 1965 and after irrigation on 20 July 1965 in Arizona, USA (after Ehrler and van Bavel 1967).

Carlson et al. (1972) observed an increase in leaf-air temperature differential corresponding to a decrease in relative water content, again a direct consequence of stomatal closure and reduced rate of evaporative cooling. Clark and Hiler (1973) suggested that leaf-air temperature differential could be used as an indicatorforthe stress-day factor.

Jackson et al. (1977) were ableto successfully describe the water status and requirements of a durum wheat crop by using plant canopy temperatures obtained with portable radiation thermometers. Air temperatures measured at 150 cm above the soil surface were subtracted from the canopy temperatures to obtain the canopy air temperature differentials (T_c-T_a). The summation of T_c-T_a over time yielded a factor termed the "Stress Degree Day" (SDD).

$$SDD = \sum_{n=1}^{N} (T_c - T_a)_n \qquad (2)$$

An expression relating evapotranspiration (ET) to net radiation (Rn) and Tc-Ta was developed:

$$ET = R_n - B\ (T_c - T_a) \qquad (3)$$

where B is a composite constant determined by using daily values of ET from the lysimeter and daily values of Rn over the lysimeter. Measured water depletion and calculated ET using Equation 3 agreed reasonably well.

It appears that leaf-temperature measurements, when obtained in conjunction with other atmospheric parameters such as net radiation, air temperature, and wind speed, could be effectively used to characterize water stress.

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Session 4

Interdisciplinary Research Needs of Agroclimatological Studies: Modeling, Approaches and Minimum Data Set

Chairman: R. C. McGinnis

Rapporteur: S. J. Reddy

Moderator
and Discussant: M. B. Russell

Interdisciplinary Research Needs of Agroclimatological Studies: Modeling Approaches and Minimum Data Set

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Summary

Agricultural production is primarily dependant upon crop variety, soil, weather and management practices. Crop weather models are useful in quantifying the response of specific production factors singly or in combinations on crop growth and development These models could be used as research tools in planning alternative strategies for cropping, land use and water management practices for a range of agroclimatic situations. Several other advantages of crop weather models are discussed in this paper. The various approaches used in crop growth, development and yield models are also described. These approaches could be generalized as regression, physiological and combination type. The merits and demerits of each of these approaches are discussed. It is believed that a dynamic crop growth and development modeling approach that utilizes input data on crop, soil and weather will be suitable to initiate the modeling studies at ICRISAT. It seems desirable to test the existing sorghum model (SORGF) developed by Arkin et al, (1976) at Texas for adoption in the SAT rather than developing new models. It is suggested that collaborative multilocation trials should be initiated to help overcome the location specificity problem. This needs an interdisciplinary approach involving the voluntary participation of specialists from different disciplines and institutions. Emphasis has been given in this paper to identify a minimum data set that needs to be collected from each center. It is hoped that data collected from these multilocation trials will be useful in developing and testing models that have wider applications.

Soil, water, and climate have a pervasive influence on crop production in the semi-arid tropics. Development of improved production technology to increase and stabilize food production in these areas requires a more complete and quantitative understanding of the time and spatial variations of these natural resources and the manner and degree to which they influence crop growth and productivity.

Quantification of the phasic development (phenology) of plants as influenced by climate is not simply a heat sum problem in the general sense, but is influenced by daylength, water deficit or excess, carbon dioxide supply, nutrient deficits, etc. Due to the effects of these factors singly and in combination, thetreatment responses in terms of crop yields often become highly specific to a particular location, genotype, management, and time. Therefore, there is an urgent need to develop an understanding for the quantification of the response functions of specific environmental factors on the growth, physiological behavior, and yield of crops. Such data can be used to develop models to predict crop yields on small and large scales.

For carrying out modeling exercises, results from diverse experimental sites with a common or standardized set of treatments and a minimum set of observed data on crop, management, soil, and meteorological factors is required. Our search for data on crops of interest to us and grown under semi-arid tropical conditions showed that few such research reports exist. In most cases adequate information on crop, soil, and management treatments is

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available but little, if any, microclimatic data are available. Reports on weather elements are generalized. We believe agroclimatologists have a very important role to play in this interdisciplinary effort.

In the dry semi-arid tropical areas, due to the characteristic distribution of the natural endowments (soils, and climate), location specificity is strongly exhibited in terms of crop-growing environment. Crop-growth models may be useful in planning alternative strategies for cropping, land use, and water management. To economists these are helpful in cost benefit ratio analysis. Definition of genetic characteristics of crops may enable plant breeders to develop crops "tailored" to different climatic and physiographic conditions. According to current evidence, minor modifications of crops or microclimate within the realm of our current biological and technological capabilities could markedly increase crop productivity. Crop-growth simulation modeling could substantially assist in an improved management-decision process for crop production, and in delineating the potentially most rewarding areas for agricultural research.

Type of Models

The various approaches used in crop growth, development, and yield models are not easily summarized. Lack of agreement between researchers on how to summarize or categorize previously reported approaches is readily apparent and is not consistent between or even within disciplines.

Newman (1974) distinguished basically between two modeling approaches: modeling based on mathematically formulated relationships with empirical constants when necessary ("deterministic approach"), and modeling involving some type of statistical-regression technique for fitting empirical relationships between climatological variables and crop-production statistics ("stochastic approach"). Jensen (1975) categorized models into three types: statistical models, state-of-the-art physiological models, and statistically based crop/weather soil-moisture models. Baier (1977) suggested three categories of models on the basis of data source, predominant purpose of the model and its potential application. The models proposed were crop-growth simulation, statistically based crop-weather analysis models, and multiple-regression models. Three categories of models were also suggested by Shaw (1977): mathematical or statistical, where a predictive equation is probably the primary interest; a biological or physical model where an explanation of why events occur and how they affect growth and/or yield (importance of each parameter) is as important or more important than the final predictive equation; and combinations of these two.

Thus it is apparent that many different approaches have been utilized by researchers — depending on their needs, sources of data, and experience. Itfollowsthatanyone attempting to add to the knowledge in this area must determine which approach might best serve his objectives.

One of the problems with statistical modeling is that the assumptions in the regression model are often not met. Regression analysis uses a least-squaretechniqueand as suchwill giveafit minimizing the sum of squares. The few observations that depart significantly from most of the data may be the points having the greatest information (drought or high-rainfall years), but will generally not be as well fitted. Many sets of data may show a significant trend over a period of years, but once this factor is put into a regression equation it may force a relatively good fit, regardless of whether it is actually associated with other independent variables or confounded with independent variables already used.

Physiological models take a more deterministic mathematical approach and should help explain how various parameters interact. For this reason, they should be useful in identifying deficiencies in our knowledge. On the other hand, it is difficult to apply these models to a large area because of data-base requirements. Some of these models are very complex in that they attempt to reconstruct the vital processes of the plant step by step. There is a limit to complexity; beyond this limit it ceases to be useful, particularly if accurate yield forecasts for large areas are desired.

Therefore, a combination approach could be more useful in the crop-growth-development and yield-modeling studies. The scientific emphasis perhaps ought to be not on the question of a model's uniqueness or even on how closely its predictions fit a particular set of data, but on the clarity with which discrepancies between model predictions and experimental data might lead to profitable new inferences.

It should be remembered that modeling is not a substitute for experimentation, but it may provide a more rational basis for experimentation. We need detailed sound and comprehensive experimentation as a basis for devising models, as well as for supplying the necessary parameters and for validating (or refuting) their results. Reciprocally, such results can help economize experimentation by showing where it is needed most.

Advantages of Modeling

Modeling of plant growth and development has a number of potential advantages, as outlined by Thornley (1976).

- A mathematical basis for hypotheses enables progress towards a quantitative understanding of plants and their responseto environment.
- An attempt at model construction can help in pinpointing areas where knowledge and data are lacking.
- Modeling can stimulate new ideas and experimental approaches.
- Modeling may lead to a reduction in the amount of ad hoc experimentation, enabling design of experiments which answer particular questions and discriminate between alternative hypotheses.
- Compared with traditional methods, models often make better use of data (which are becoming increasingly precise but more expensive to obtain).
- Information on different aspects of plant growth can often be brought together, providing a unified picture and sometimes a valuable stimulus to collaboration and team work.
- A model frequently provides a convenient data summary.
- Models can give a method for interpolation, extrapolation, and prediction.
- A successful model may be used to suggest priorities for applied research and development and, if used cautiously, to aid the crop manager in making decisions.

Current Status of Modeling

A great deal of modeling work has been directed to individual processes involved in crop growth and development such as modeling evaporation (Ritchie 1972), photosynthesis (Duncan et al. 1967), respiration (Baker et al. 1972), water balance (Baier and Dyer 1978), probability of occurrence of particular weather events (Virmani et al. 1978),technological effect (Thompson 1969), etc. Growth-simulation models are available for corn (Splinter 1973), soybean (Curry et al. 1975), cotton (Stapleton et al. 1973), alfalfa (Miles et al. 1973), wheat (Rickman et al. 1975), and sorghum (Arkin et al. 1976). Few, if any, crop-growth models are at present being used for management decision-making, they are primarily research tools.

One of the major problems in modeling work is the specificity exhibited by a particular model with respect to crop and location. Modeling scientists are much concerned about this problem. (Suggestions are sought from participant scientists regarding remedial measures for overcoming this problem.) At this time, we visualize that a multilocation experiment could be useful. A variety of climatic, crop, and soil environments can be obtained by using few SAT bench-mark locations as experimental sites. Data from these areas could be pooled and mathematical and statistical analysis employed to build a model with (probably) wider applications.

Suggested Approach

We believe that dynamic crop-growth modeling will suit our purpose. In this kind of approach, the inputs to the model include the crop, soil, and weather factors affecting crop yields. Physiological data enable the model to identify plant traits, including such parameters as leaf number and leaf area; environmental data, such as daily weather variables, allow the modeled plant to produce a specific response to its surroundings. Examples would include the rate at which the plant grows and develops; data on rowspacings, plant populations, etc. relate the modeled plant to surrounding field community. In most cases daily ET and PET are calculated and these are used for generating a water balance. Wherever open-pan data are available, these could be used directly as a measure of Eo or PET.

In crop-weather modeling, where we are dealing with the biological system, the model should have the capability of updating the *computation at any point in the growing season,* i.e., a feedback capability. This would represent a very important feature in its operational application, in which the development of a field crop is observed through the growing season (Maas and Arkin, 1978). The basic crop-growth model should, however, simulate the growth, development, and yield.

Proposal for a Multilocation Experiment

We are keen on getting your suggestions regarding the minimum amount of data to be collected to derive the growth, development, and yield model for sorghum. Arkin et al. (1976) suggested the following Input data for the sorghum model.

Table 1. Input data required for a sorghum-simulation model.

Plant Data
- Leaf number-total number of leaves produced
- Leaf area - maximum area of each individual leaf (cm^2)

Planting data
- Planting date, month, day, year
- Plant population (plants/ha)
- Row width (cm)
- Row direction (degrees)

Climatic data (daily, from planting to maturity)
- Maximum temperature CO
- Minimum temperature (°C)
- Solar radiation (ly/day)
- Rainfall (cm/day)

Soil data
- Available water-holding capacity (cm)
- Initial available water content (cm)

Location data
- Latitude (degrees)

Shaw(1963) utilized Class-A pan-evaporation data instead of solar radiation for the Iowa corn model. We have not come across work where these were compared for tropical areas. Utilization of Class-A pan data has the advantage that most of the meteorological services have recorded it for fairly long periods. It integrates meteorological factors (radiation, temperature, humidity, and wind) which mainly cause evaporation.

We feel there is a need for interdisciplinary research for crops in the semi-arid tropical regions. We propose the following experiment for your consideration and discussion.

Table 2. Proposal for multilocational experiment.

Crop	:	Sorghum
Varieties	:	One to three (depending upon availability of cultivars; tolerant, intermediate, and susceptible to drought).
Treatments	:	Two to four moisture regimes
Replications	:	Three
Met data collection	:	Daily solar radiation Pan evaporation Rainfall Temperature
Crop data	:	Dry weight at important phenological stages LAI, leaf number, light interception, and days to flowering.
Soil data	:	Moisture characteristics Depth Initial moisture and final moisture Moisture at two other stages during growing season.
Location	:	Some SAT locations

Conclusions

Generation of a suitable crop-production technology for increased and stabilized crop production in the seasonally dry semi-arid tropics — spread over large areas characterized by a variety of agroclimatic conditions — needs a thorough understanding of the soil-plant-atmosphere continuum. Often experiments involving one or two treatments give excellent single-factor response functions, but with the addition of a few essential variables could give a holistic explanation. Hence it is essential to identify a minimum data set required for an integration of different response functions in the simulation of plant growth and development. It is obvious that interdisciplinary studies involving agroclimatologists, crop physiologists, soil physicists, and crop simulators would go a long way in such an understanding.

Multilocation experiments now being proposed could help us include a wide variety of agroclimatic situations in a single model and would aid immensely in our efforts to overcome the problem of location specificity.

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Appendix I

Text of French Papers

Bilan Hydrique et Periode Frequentielle de Vegetation

P. Franquin*

Résumé

S'il fait appel à un modèle stochastique, le bilan hydrique est très coûteux. A condition que l'échantillon pluviométrique soit assez important, une solution est de se contenter de faire l'analyse statistique des sorties. Mais le bilan hydrique est encore très coûteux parce qu'il restitue une information généralement très spécialisée, dont le champ d'application est donc forcément limité. Une solution à cet inconvénient consiste à établir un modèle probabiliste de la période de végétation, modèle qui intègre ensemble des caractéristiques de climat et des caractéristiques de sol, permet d'étendre les résultats d'une simulation de bilans hydriques de l'ensemble des cultures, des sols et des pratiques culturales d'une région couverte par une même station climatique.

Un Modèle de Bilan Hydrique

Les pluies sont toujours aléatoires, même en régions humides. Et comme un déficit, un excès d'eau peut être très dommageable pour la culture, même en régions arides, en particulier dans la pratique de l'irrigation complémentaire aux pluies. Pour rendre compte du caractère aléatoire des ressources en eau, un modèle de bilan hydrique devrait être de nature stochastique. Mais un système stochastique s'accommoderait mal d'un pas de temps de 5, 7 ou 10 jours, parce qu'il n'y a pas indépendance des distributions de fréquences des pluies entre des intervalles de temps aussi courts: il y a un effet de persistance. De plus, générer des pluies au hasard à partir de 73, 52 ou 36 distributions de fréquences (sur une année entière) — qui plus est, compte tenu de la persistance – serait très lourd et extrêmement onéreux. Or, pour servir réellement, un programme de bilan hydrique doit être d'un usage aussi peu coûteux que possible. Ce sera le cas avec un modèle déterministe qui rendra les mêmes services qu'un modèle stochastique pourvu que l'échantillon pluviométrique soit suffisamment important. L'analyse statistique est alors appliquée aux sorties, au lieu de l'être aux entrées.

C'est ainsi qu'a été conçu ORBVCR, celui des modèles de bilan hydrique de l'ORSTOM qui est adapté aux régions à tendance aride. Dans ces régions, les cultures partent en végétation sur un sol dont le profil, desséché plus ou moins profondément avant le retour des pluies, va se réhumecter progressivement vers le bas. Pour simuler ce processus de réhumectation, on compartimente habituellement le sol en réservoirs qui s'alimentent en cascade. Mais, encore ici, le procédé est trop onéreux. La seule originalité de ORBVCR, par rapport à ce genre de modèles, c'est de faire appel à un système extrêmement simple de simulation de la réhumectation progressive.

Pour le reste, ORBVCR use de la relation d'Eagleman pour le calcul de l'évapotranspiration réelle (ETR). Conçu dans l'optique d'un niveau technique de l'agriculture relativement élevé, le système ne prédit la ruisselle que pour la partie des fortes pluies qui est en excès de la capacité maximale de mise en réserve (RU). Il permet encore le départ du bilan à date fixe ou à partir d'une période de 5,7 ou 10 jours totalisant une hauteur de pluie donnée, compte tenu ou non d'une certaine quantité d'eau présente au départ. Des quantités d'eau d'irrigation à dates fixes peuvent être ajoutées aux pluies. Enfin le

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système est muni de coefficients de réglage permettant de l'amener à s'ajuster au mieux à des données d'observation des variations de l'humidité du sol.

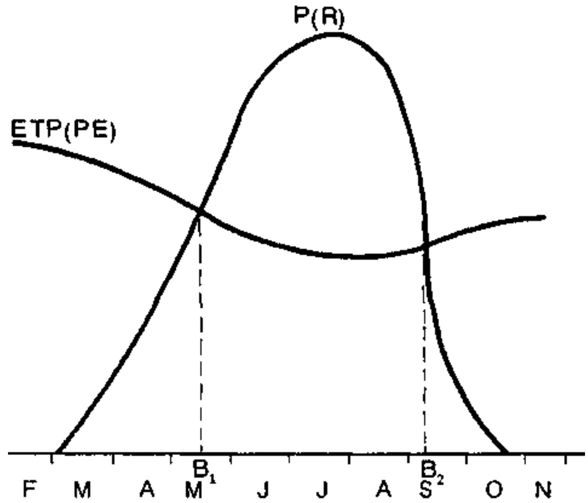
Période Fréquentielle de Végétation

Si le bilan hydrique est d'usage onéreux, c'est aussi parce qu'il restitue une information élaborée, forcément spécialisée, dont le champ d'application sera donc moins étendu que celui d'une information plus rudimentaire. En termes de simples hauteurs de pluie, on approchera, au moins dans un premier temps, tous les problèmes de nature hydrique qui se posent à l'agriculture; l'impact d'un bilan hydrique établi pour un cultivar de cycle de végétation défini, semé à une époque déterminée sur un sol de caractéristiques hydriques données, sera par contre nécessairement plus étroit.

Une solution, pourtant, permet de généraliser à l'ensemble des cultures, des sols et des opérations culturales d'une région couverte par une même station climatique, les résultats d'une simulation de bilans établis pour une série suffisamment longue d'années. Cette solution passe par la notion de "période fréquentielle de végétation."

Ce dernier concept répond à l'intérêt de réduire à une seule expression, aussi synthétique que possible, la relation entre climat et production, ne serait-ce d'ailleurs qu'en raison des difficultés que soulèvent les probabilités composées. L'expression *synthétique la plus* achevée, parce qu'elle intègre tous les éléments qui participent à la production, est la "période de végétation." Or, tandis que cette entité intègre de façon continue ces mêmes éléments, son traitement statistique ne peut procéder que de façon discontinue: notamment, en ne considérant, dans son déroulement, qu'un certain nombre d'évènements remarquables.

C'est un événement remarquable pour. le découpage, dans le cycle annuel, de la période de végétation, tout événement, climatique ou phénologique, dont l'intérêt répond à un objectif. Il pourra doncy avoir, en un même point, autant de périodes de végétation en partie différentes que de projects spécifiques. Pourtant, il est possible de donner à cette entité rationnelle un caractère de généralité si l'on considère des événements climatiques valables dans tous les cas, comme par exemple les instants où se recoupent (Graphique 1) les courbes d'évapotranspiration potentielle (ETP) et de pluviométrie (P). Mais surtout, en lui conférant *l'expression fréquentielle*, laquelle permettra de choisir un niveau de risque en rapport avec tout problème spécifique.



Graphique 1. Une relation généralisée entre la pluviométrie et l'évapotranspiration.

Cette expression fréquentielle de la période de végétation s'inscrit dans un système de coordonnées dont l'axe des abscisses est celui du temps, l'axe des ordonnées étant une échelle de fréquences relatives. Dans ce système, la variabilité de chacun des événements remarquables qui caractérisent la période de végétation peut être figurée (Graphique 2A):

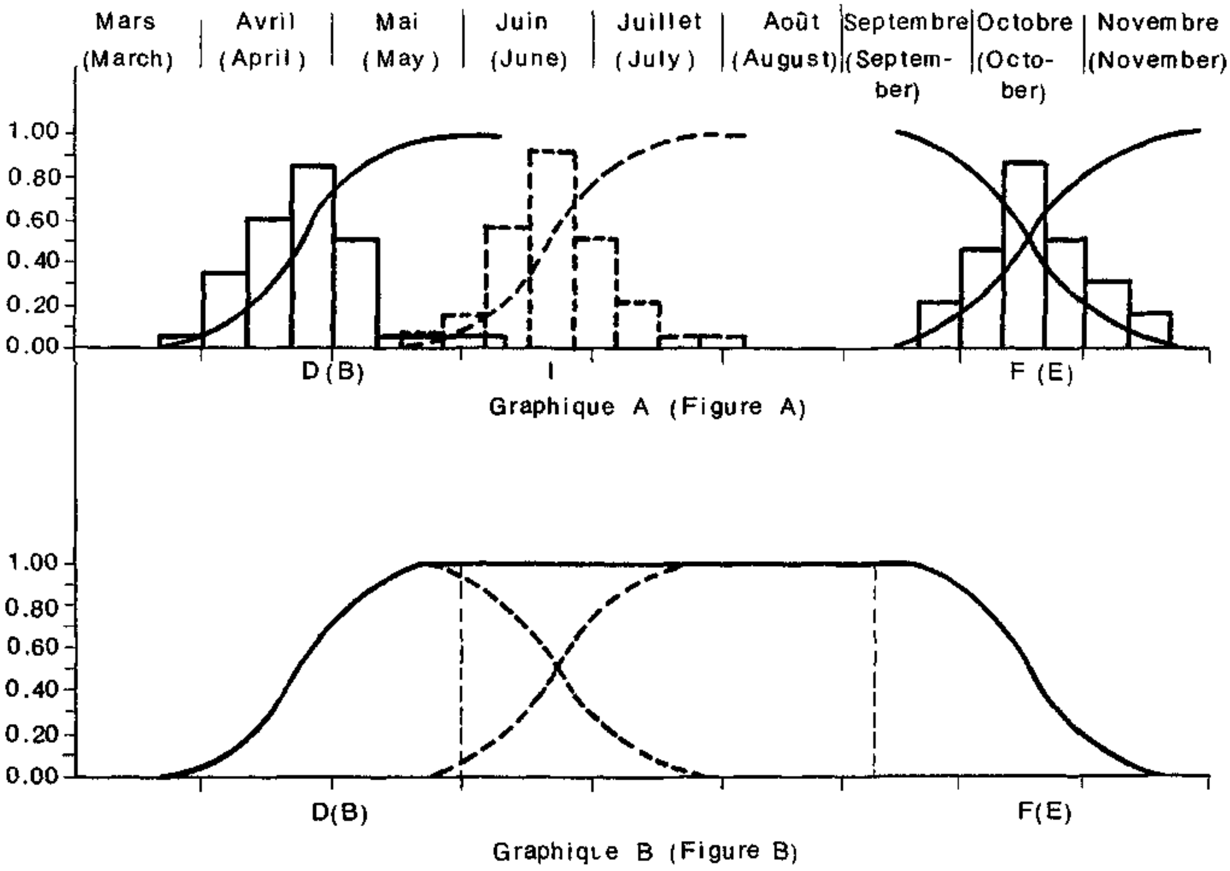
- par un histogramme de fréquences construit sur un intervalle de temps de 10 jours, par exemple.
- par un polygone intégral de fréquences relatives, ou une courbe sigmoïdale de probabilités totales si l'échantillon est assez important pour être représentatif de la population générale.

La période de végétation sera donc jalonnée de distributions de fréquences (histogrammes mais surtout sigmoïdes) qui, prises 2 à 2, successivement ou non, délimitent des périodes et sous-périodes. Soit, par exemple, es événements D (début) et F (fin) de la période considérée: la sigmoïde D donne les probabilités qu'elle soit *déjà ouverte* à toute date donnée; la sigmoïde F, les probabilités qu'elle soit *déjà fermée*. Mais ce qui nous intéresse, ce sont les probabilités qu'elle soit *encore ouverte*: elles seront données par la sigmoïde symétrique de F (Fig. 2). On pourra de même construire les symétriques des sigmoïdes des événements intermédiaires I (Graphique 2B).

L'intérêt de ce modèle géométrique réside dans l'intégration de la variabilité de la position et de la durée de la période de végétation que réalisent l'aire et la forme de la surface délimitée par deux sigmoïdes. Il donne d'abord une "vue" de toutes les périodes de végétation possibles, avec la probabilité composée (produit des deux probabilités élémentaires), si les événements sont indépendants ou peu corrélés, qu'elle soit ouverte entre deux dates quelconques. Il constitue par ailleurs le cadre statistique dans lequel vont se dérouler toutes les opérations du calendrier cultural, avec leurs chances de réussite. De la forme et des dimensions de cette surface dépend aussi la vocation d'une culture ou d'un cultivar à s'adapter aux conditions ainsi figurées entre les deux sigmoïdes, en rapport avec le calage de son cycle qui présente la meilleure probabilité. Enfin si, comme ce sera le cas en régions tropicales, le modèle a été construit en termes de probabilités de dépassement de niveaux d'ETP par les pluies (ou de niveaux de ETR/ETP), l'aire de la surface, que l'on pourra pondérer encore par un facteur radiatif de production photosynthétique, représentera une capacité de production de matière sèche: ce sera un indice climatique relatif de productivité.

Bilan Hydrique et Période Fréquentielle de Végétation

Ce modèle peut être construit, en termes hyd-

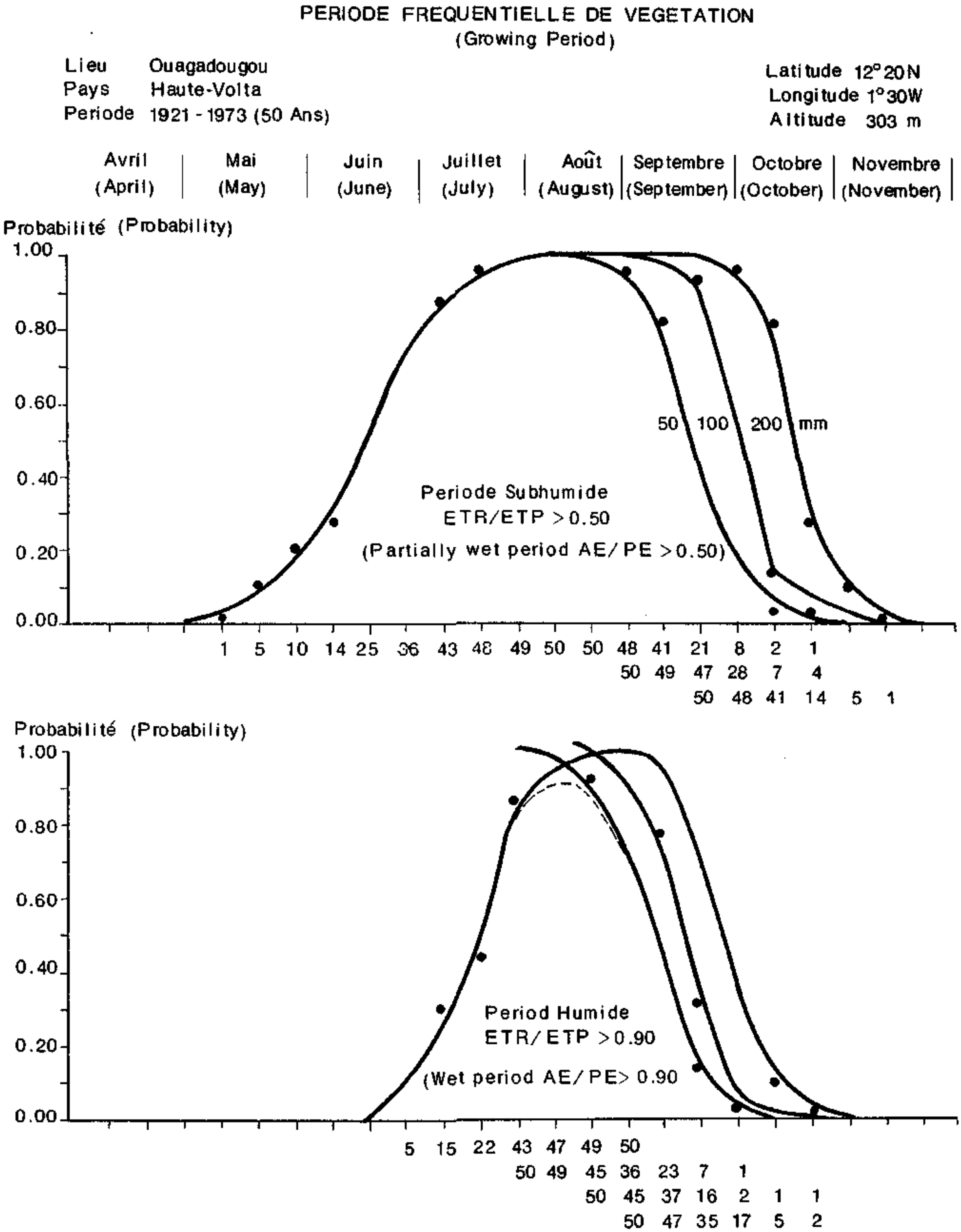


Graphique 2A et B. Des histogrammes représentant le temps et la durée d'une période de végétation.

Tableau 1. Simulation de bilan hydrique pour les périodes de 10 jours pour l'année 1973 à Ouagadougou, Haute-Volta.

Périodes		P	I	HD	HR	ETP	K	ETM	ETR	RS	RDR	RDRC	D(RS)	D(RS)/RU	ETR/ETP	ETM-ETR	RU[1]
Juin	1ère	55.2	.0	55.2	1.00	69.0	.50	34.5	34.5	20.7	.0	.0	34.5	.62	.50	.0	55.2
Juin	2ème	7.5	.0	28.2	.51	64.0	.50	32.0	28.2	.0	.0	.0	55.2	1.00	.44	3.8	55.2
Juin	3ème	24.9	.0	24.9	.45	62.0	.55	34.1	24.9	.0	.0	.0	55.2	1.00	.40	9.2	55.2
Juil	1ère	14.5	.0	14.5	.26	60.0	.60	36.0	14.5	.0	.0	.0	55.2	1.00	.24	21.5	55.2
Juil	2ème	49.4	.0	49.4	.89	58.0	.70	40.6	40.6	8.8	.0	.0	46.4	.84	.70	.0	55.2
Juil	3ème	214.5	.0	100.0	1.00	60.5	.85	51.4	51.4	48.6	123.3	123.0	51.4	.51	.85	.0	100.0
Août	1ère	44.2	.0	92.8	.93	53.0	1.00	53.0	52.1	40.7	.0	123.0	59.3	.59	.98	.9	100.0
Août	2ème	84.2	.0	100.0	1.00	50.0	1.00	50.0	49.8	50.2	24.9	148.2	49.8	.50	1.00	.2	100.0
Août	3ème	38.7	.0	88.9	.89	55.0	1.00	55.0	53.5	35.4	.0	148.2	64.6	.65	.97	1.5	100.0
Sept	1ère	20.4	.0	55.8	.56	51.0	1.00	51.0	39.9	15.9	.0	148.2	84.1	.84	.78	11.1	100.0
Sept	2ème	34.4	.0	50.3	.50	51.0	1.00	51.0	37.4	12.9	.0	148.2	87.1	.87	.73	13.6	100.0
Sept	3ème	25.6	.0	38.5	.39	53.0	1.00	53.0	31.5	7.0	.0	148.2	93.0	.93	.59	21.5	100.0
Oct	1ère	30.3	.0	37.3	.37	56.0	1.00	56.0	30.9	6.4	.0	148.2	93.6	.94	.55	25.1	100.0
Oct	2ème	.0	.0	6.4	.06	58.0	1.00	58.0	6.4	.0	.0	148.2	100.0	1.00	.11	51.6	100.0
Oct	3ème	1.4	.0	1.4	.01	61.6	1.00	61.6	1.4	.0	.0	148.2	100.0	1.00	.02	60.2	100.0
Nov	1ère	.0	.0	.0	.00	53.0	1.00	53.0	.0	.0	.0	148.2	100.0	1.00	.00	53.0	100.0
Nov	2ème	.0	.0	.0	.00	51.0	1.00	51.0	.0	.0	.0	148.2	100.0	1.00	.00	51.0	100.0
Nov	3ème	.0	.0	.0	.00	50.0	1.00	50.0	.0	.0	.0	148.2	100.0	1.00	.00	50.0	100.0
Déc	1ère	.0	.0	.0	.00	50.0	1.00	50.0	.0	.0	.0	148.2	100.0	1.00	.00	50.0	100.0
Déc	2ème	.0	.0	.0	.00	49.0	1.00	49.0	.0	.0	.0	148.2	100.0	1.00	.00	49.0	100.0
Déc	3ème	.0	.0	.0	.00	56.1	1.00	56.1	.0	.0	.0	148.2	100.0	1.00	.00	56.1	100.0
Total		645.2	.0			1171.2		1026.3	497.0							529.3	

1. RU maximale = 100 mm
Bilan Climatique: total pluie − total ETP = −526.0 mm



Graphique 3. La longueur probable des périodes semi-humide (ETR/ETP 0.50) et humide (ETR/ETP 0,90) chez trois sols à Ouagadougou, le Haute-Volta, à partir de 1921 à 1973.

riques ou énergétiques, à partir d'une information tout à fait élémentaire, comme de simples hauteurs pluviométriques ou des températures; ou à partir d'une information plus complète, comme des valeurs du rapport P/ETP; ou encore à partir d'une information très élaborée, comme celle qui résulte de la simulation de bilans hydriques. Le bilan hydrique, parce qu'il implique la définition d'une RU (capacité maximale utilisable de l'eau du sol), permet dans une certaine mesure d'incorporer au modèle les caractéristiques du sol qui déterminent, pour une culture, la valeur de la RU. On pourra construire le modèle pour une RU donnée, en particulier lorsque l'on aura pu régler le modèle du bilan sur des observations des variations de l'humidité du sol. Mais on pourra aussi le construire, pour des applications plus générales, sur la base de plusieurs RU: 50, 100 et 200 mm par exemple, ce qui permettra d'interpoler les résultats pour des RU intermédiaires observées: 80 ou 130 mm, par exemple.

Un exemple de simulation de bilan hydrique, pour l'année 1973 à Ouagadougou, avec une RU de 100 mm, est présenté en Tableau 1. Sur la base de telles simulations pour un nombre d'années suffisamment grand (au moins 30), il sera possible, selon les besoins, de construire des modèles fréquentiels en termes de ETR (évapotranspiration réelle), ETP-ETR ou ETM-ETR (déficit en eau de la culture), RS (eau du sol) . . . Mais c'est le rapport ETR/ETP (évapotranspiration relative) qui surtout nous intéresse car ce rapport est un indice des disponibilités en eau qui conditionne de façon linéaire la production de matière sèche.

Dans le cas de cultures annuelles (graminées, arachide, cotonnier, etc . . .), il sera généralement suffisant de considérer deux niveaux du rapport ETR/ETP: l'un situé au voisinage de 0,50 parce qu'il correspond aux conditions minimales requises pour assurer l'établissement de la culture (germination-levée-seedling) et sa maturation; l'autre, au voisinage de 1,00 parce qu'il correspond aux conditions requises pour assurer le développement fructifère. On peut voir, en Graphique 3, un modèle fréquentiel de la période de végétation construit pour Ouagadougou:

- d'une part sur la base des probabilités de dépassement de 0,50 (ETR/ETP). Les sigmoïdes d'ouverture et de fermeture définissent en fréquence ce que l'on peut nommer la période "semi-humide" pour les RU: 50, 100 et 200 mm.
- d'autre part pour les probabilités de dépassement de 0,90 (ETR/ETP). Les sigmoïdes délimitent en fréquence ce que l'on peut nommer la "période humide," pour les mêmes valeurs de la RU.

Entre les sigmoïdes de fermeture (les sigmoïdes d'ouverture sont pratiquement identiques quelle que soit la RU), on pourra interpoler d'autres sigmoïdes correspondant à des RU intermédiaires.

Concernant des cultures, annuelles ou permanentes, dont on exploite non pas l'appareil fructifère mais l'appareil végétatif, lequel est le produit direct de l'élaboration de la matière sèche, on pourra prendre en considération de plus nombreux niveaux de ETR/ETP, par exemple: 0,20 – 0,40 – 0,60 – 0,80 – 1,00 – 1,20, etc . . .

Parce qu'il est statistique et qu'il permet donc de se fixer des niveaux de risque climatique variables selon le problème particulier considéré, ce modèle de la période de végétation peut effectivement être généralisé à l'ensemble des cultures, des opérations culturales et des sols d'une région couverte par une même station climatique.

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Besoins en Eau et Adaptation du Mil à la Saison des Pluies au Sénégal

C. Dancette*

Résumé

Les besoins en eau du mil (Pennisetum typhoïdes) ont été mesurés au CNRA de Bambey, entre 1973 et 1977. Des variétés de 75, 90 et 120 jours ont été testées. En gros, les besoins en eau sont directement proportionnels à la durée du cycle végétatif. En ce qui concerne les rendements en grain et en paille, les choses sont beaucoup moins simples, surtout si on considère la quantité d'eau nécessaire pour produire 1 kg de matière sèche. Les résultats sont interprétés dans une optique d'économie de l'eau et d'adaptation aux conditions pluviométriques marginales. On ne se borne pas à l'énumération des résultats obtenus ponctuellement, mais on essaie de les généraliser à l'ensemble du Sénégal, à partir de la caractérisation de la demande évaporative (gradient Nord-Sud notamment).

L'alimentation hydrique n'est pas étudiée seulement en conditions optimales (avec irrigation complémentaire, pour la mesure des besoins en eau optimaux ou ETM.) mais aussi en conditions hydriques limitantes; l'incidence des stress hydriques sur les rendements en grain et en paille est chiffrée lorsque les conditions pluviométriques et les variétés s'y prêtent. Quelques orientations de travail sont données quant à l'utilisation pratique au niveau de la recherche et du développement, des résultats obtenus.

Introduction

Le mil pénicillaire (*Pennisetum typhoïdes*) constitue la céréale de base du Sénégal, au point de vue alimentaire. On estime ainsi, en Pays Sérère, qu'il faut en moyenne 400g de mil par jour et par personne, pour satisfaire les besoins de nourriture (A. F. BILQUEZ 1975); cultivés sur plus de 600.000 ha, ces mils ont des rendements très médiocres (520 kg/ha, en moyenne), alors que les arachides peuvent dépasser couramment 1.000 kg de gousse/ha, soit autour de 730 kg de graine.

Si l'incitation à produire du mil est forte pour les paysans en ce qui concerne l'autoconsommation, elle est par contre faible actuellement sur le plan financier: 36 F CFA/kg de grain pour le mil, au lieu de 42 F/kg de gousse d'arachide, sur le marché officiel en 1977 avec, nous l'avons vu, des rendements bien plus faibles. Il n'en demeure pas moins que le cultivateur a toujours intérêt à améliorer ses rendements de mil, soit pour se garantir une meilleure autosuffisance alimentaire, soit pour consacrer des superficies plus grandes à des cultures plus rentables (arachide, coton, niébé . . .). De plus, la situation du mil pourrait évoluer très vite, dans un sens favorable à la fois pour l'Etat et pour le cultivateur, par la politique des prix d'une part et par l'amélioration de la technologie du mil d'autre part (stockage, battage, broyage, utilisation pour la panification etc . . .).

Sur le plan purement agronomique, l'augmentation des rendements de mil peut être très raisonnablement envisagée à partir des efforts actuels de la recherche, dans les domaines de la sélection, des techniques culturales, de la fertilisation et des traitements phytosanitaires entre autres.

Les besoins en eau du mil et l'adaptation

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rationnelle de cette culture aux conditions sénégalaises de sol et de pluviométrie font l'objet de la présente communication. La connaissance des besoins en eau optimaux, ou évapotranspiration maximale ETM., et de la courbe de réponse du mil aux stress hydriques subis pendant son cycle de végétation, conditionne en particulier une meilleure compréhension de la production du mil et par là, de meilleurs choix (variétés, techniques culturales . . .) au niveau de la recherche et de la vulgarisation.

Besoins en Eau du Mil (ETM) Mesurés au CNRA de Bambey

Conditions Générales

Les besoins en eau du mil ont été mesurés entre 1973 et 1977, au CNRA de Bambey, dans la zone centrale du Sénégal. Les variétés testées avaient des longueurs de cycle végétatif de 75, 90 et enfin 120 jours.

Les cultures étaient réalisées en grandes parcelles de 196 m² (4 répétitions) et en bonnes conditions agronomiques (fumure forte préconisées, labours, traitement phytosanitaire, propreté, gardiennage contre les oiseaux, etc . . .). Le sol était qualifié de sableux, ferrugineux tropical, faiblement lessivé, d'appellation vernaculaire: DIOR, et profond.

Les écartements étaient ceux recommandés par la recherche et par la vulgarisation: 100 cm sur 100 cm pour le mil Souna de 90 jours en 1973 et 1974; 50 cm sur 20 cm en 1974, puis 45 cm sur 15 cm en 1975, pour le mil nain de 75 jours du GAM (Group d'amélioration des mils); 90 cm sur 90 cm en 1976, puis 100 cm sur 100 cm en 1977, pour les mils sanio de 120 jours.

L'irrigation en complément des pluies était réalisée par aspersion au moyen de sprinklers d'angle, à secteur réglable; les apports d'eau étaient contrôlés au moyen de pluviomètres installés juste au-dessus de la végétation.

Les bilans de consommation étaient effectuées de deux façons différentes:

1. En place, au moyen de tubes d'accès de 4 m de profondeur et de relevés périodiques (hebdomadaires le plus souvent) d'humidité du sol au moyen d'humidimètres à neutrons français ou américains, fournis par l'Agence internationale de l'énergie atomique (AIEA), par la Coopération française (assistance spéciale GERDAT) et enfin par le Centre d'énergie nucléaire de Cadorache (France). A chaque campagne, on partait d'un sol asséché au maximum, sur la plus grande profondeur possible. En 1976 et 1977, les flux ont été contrôlés par des tensiomètres "soil moisture" (aide AIEA.) installés soit verticalement jusqu'à 150 cm de profondeur, soit horizontalement, de 150 à 400 cm de profondeur, à partir d'une fosse. Les mesures de bilan hydrique ont été facilitées par des saisons des pluies exceptionnellement déficitaires et telles que le sol n'était pas humecté profondément (moins de 250 cm et le plus souvent moins de 150 cm). Le bilan hydrique pouvait donc être maitrisé facilement au moyen d'irrigations non excessives, sans percolations incontrôlées et sans ruissellement (lames verticales de protection autour des tubages).
2. Au moyen de cuves de végétation (évapotranspiromètres) de 4 m² de surface et 1 m de profondeur. Dans l'ensemble, après une première campagne "à blanc" de mise en place et de contrôle (en 1972), les évapotranspiromètres qui étaient prévus pour relayer éventuellement la première methode "en place," en cas de pluies excédentaires ou même normales et de percolations incontrôlables, n'ont pas donné de résultats très différents de cette première méthode de bilan hydrique. Il apparait même, au terme de ces cinq années déficitaires en pluie, que nous aurions pu nous dispenser de l'utilisation des évapotranspiromètres, ce qui n'était pas évident au départ et qui pourrait être infirmé par des saisons plus pluvieuses. A noter que des tubages d'accès pour la sonde à neutrons étaient installés au milieu des cuves et permettaient de faire des bilans classiques de consommation, en attendant un drainage gravitaire naturel des cuves. En effect, il s'avère que la saturation des cuves dès le debut de la culture, afin d'assurer le drainage et de procéder au bilan classique, n'est pas souhaitable et peut induire des différences de traitement et donc de comportement des plantes, par rapport au reste de la parcelle de garde.

En plus du traitement ETM., il y avait aussi un traitement ETR. (evapotranspiration réelle) sans irrigation de complément et qui pouvait donc être plus ou moins stressé, selon les pluies reçues. Nous en reparlerons à propos de la satisfaction des besoins en eau du mil.

Principaux Résultats

Nous en donnerons un résumé seulement. En effet, d'autres résultats partiels mais détaillés, peuvent être consultés par ailleurs en ce qui concerne les mils à cycle court (DANCETTE 1975). Dans le Tableau 1, les chiffres indiqués sont une moyenne de quatre répétitions; précisons à ce sujet que les coefficients de variation sont le plus souvent inférieurs à 10% pour les consommations hydriques globales et pour les rendements en grain et en paille (voir Tableau 5). Les rendements en grain sont parfois moins homogènes que ceux en paille, car les dégats dûs aux oiseaux ne peuvent pas toujours être complètement évités.

Variations Inter-annuelles de l'ETM Globales, pour une Même Variété de Mil

D'une année à l'autre et avec la même variété testée, on peut noter des différences dans les besoins en eau mesurés. Il peut y avoir certes de légères modifications dans les pratiques culturales, dans la répartition des pluies et irrigations et dans le parasitisme, mais ce qui peut varier surtout, c'est la demande évaporative. C'est pourquoi nous estimons jour par jour cette demande évaporative, au moyen de mesures d'évaporation potentielle d'eau libre en bac normalisé classe A (modèle O.M.M.) et nous la raccordons pour des périodes correspondantes, aux consommations hydriques des cultures.

Ainsi, nous l'avons mesurée de 1972 à 1977 compris, pour des durées de 75, 90, 105 et 120 jours, correspondant aux cycles végétatifs des principales cultures. Dans le Tableau 2, nous avons reporté les cumuls d'évaporation bac en mm, pour les périodes mentionnées, et entre parenthèses, un indice qui caractérise cette

Tableau 1. Principaux résultats obtenus sur les mils de 120 à 75 jours de cycle.

Culture	Cycle (jours)	Année	Pluviométrie (mm)	Traitement	Besoins en eau ou ETM (mm)	Rendements (kg/ha) Grain	Rachis	Paille
						Humidité entre parenthèses		
Mil Sanio (souche Maka)	120	1976	399	Arrosé (ETM.) i = 215 mm	562 K = 0,75[1]	2035 (7,5%)	1426 (10,1%)	13 950 (3,2%)
Mil Sanio (souche Bambey)	120	1977	374	Arrosé (ETM) i = 283 mm	628 K = 0,77	1623 (3,5%)	1388 (4,0%)	14 425 (7,5%)
Mil Souna III	90	1973	400	Arrosé (ETM) i = 68 mm	417 K = 0,72	2690 (7,8%)	1360 (7,8%)	6 680 (4,3%)
Mil Souna III	90	1974	492	Arrosé (ETM) i = 73 mm	416 K = 0,74	2948 (5,4%)	1600 (5,4%)	5 760 (5,2%)
Mil GAM.	75	1974	447	Arrosé (ETM) i = 51 mm	320 K = 0,67	2151 (9,0%)	2165 (9,0%)	5 943 (8,4%)
Mil GAM. (structure céréalière)	75	1975	510	Non arrosé (ETR = ETM) (pluies excédentaires)	327 K = 0,63	1721 (9,2%)	1395 (9,2%)	5 652 (10,2%)

1. $K = \frac{ETM.}{Ev\ bac}$

Tableau 2. Evaporation d'eau libre en bac normalisé classe A, cumulée en mm, à Bambey.

Période	Année 1972	1973	1974	1975	1976	1977	Moyenne 1972–77
75 jours	550 (1,12)	486 (0,99)	477 (0,98)	438 (0,90)	489 (1,00)	496 (1,01)	489
90 jours	631 (1,10)	583 (1,02)	564 (0,99)	523 (0,91)	560 (0,98)	573 (1,00)	572
105 jours	722 (1,06)	702 (1,03)	695 (1,02)	620 (0,91)	648 (0,95)	687 (1,01)	679
120 jours	811 (1,03)	817 (1,04)	809 (1,03)	714 (0,91)	744 (0,95)	812 (1,03)	785
Date de 1ère pluie utile	5 Juin	2 Juil	12 Juil	7 Juil	13 Juil	7 Juil	

demande évaporative, par rapport à la moyenne 1972–1977. Notons que les coefficients de variation vont de 5% pour des durées de 120 jours, à 7% pour des durées de 75 jours.

Pour toute comparaison, l'idéal est donc de prendre comme référence cette evaporation bac. Si l'on compare ainsi les deux cultures de mil Sanio de 120 jours, on constate que les besoins en eau ont été:

en 1976, de 562 mm, pour une évaporation bac de 774 mm et un indice de 0,95
en 1977, de 628 mm, pour une évaporation bac de 812 mm et un indice de 1,03.

Cependant, le coefficient global $K = \frac{ETM}{Ev\ bac}$ reste voisin à 0,75 en 1976 et à 0,77 en 1977. En se ramenant à la demande évaporative moyenne (1972–1977) et à l'indice 1,00, on trouve respectivement des besoins hydriques de:

$\frac{562}{0,95} = 592$ mm en 1976 et $\frac{628}{1,03} = 610$ mm, en 1977

Les résultants deviennent donc très comparables et voisins, avec des écarts bien en dessous des erreurs d'ordre expérimental possibles: besoins en eau mesurés en gros à ±8% près, lorsque le maximum de précautions est pris.

Bien que les variations de demande évaporative, d'une année à l'autre, soient de cet ordre de grandeur et même inférieures, ce n'est pas une raison suffisante pour ne pas en tenir compte lorsqu'on le peut. Ainsi, les besoins en eau globaux peuvent être actuellement évalués de la sorte, en les ramenant à la demande évaporative moyenne (1972–1977).

- Mil Sanio de 120 jours:
  On fera la moyenne entre 592 et 610 mm, soit en gros 600 mm
- Mil Souna de 90 jours:
  On retiendra la moyenne entre $\frac{417}{1,02} = 409$
  et $\frac{416}{0,99} = 420$ soit environ 415 mm
- Mil nain de 75 jours:
  Là, les écarts sont un peu plus grands, compte tenu du fait que les variétés n'étaient pas encore bien fixées en 1974 et 1975 et, qu'entre ces deux années, on avait changé de matériel végétal, en adoptant un composite d'architecture légèrement différente (structure dite céréalière). On peut cependant retenir valablement la moyenne entre:

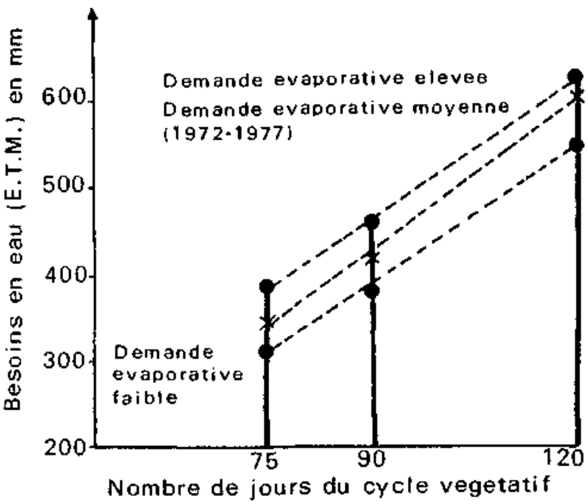
  $\frac{320}{0,98} = 327$ et $\frac{327}{0,90} = 363$, soit 345 mm

De la même façon, nous pouvons caractériser les extrêmes, compte tenu des demandes évaporatives les plus fortes et les plus faibles, enregistrées au cours de ces 6 années. On retiendra en définitive les chiffres du Tableau 3, en attendant de disposer d'une période d'observation plus longue.

Ceci peut être mis sous forme graphique (Graphique 1).

Tableau 3. Variations des besoins en eau en fonction de la durée du cycle végétatif et de la demande evaporative au CNRA, Bambey.

	ETM minimale	ETM moyenne	ETM maximale
Mil Sanio de 120 jours	546	600	624
Mil Souna de 90 jours	378	415	457
Mil nain de 75 jours	311	345	386



Graphique 1. Variations des besoins en eau globaux du mil en fonction de la durée du cycle végétatif et de la demande évaporative, au CNRA Bambey.

Variation de l'ETM du Mil et des Facteurs Culturaux K, au cours d'un Meme Cycle Cultural

La demande évaporative varie au cours de la saison des pluies: très forte au début (jusqu'à 8 mm par jour d'évaporation bac à Bambey, en juin), elle diminue ensuite avec l'installation des pluies et avec l'augmentation de l'humidité ambiante (4 à 4, 5 mm/jour en septembre), puis elle remonte avec le ralentissement des pluies (7 à 8 mm en octobre).

Elle peut subir des fluctuations brusques, du fait des sécheresses anormales en cours de saison, ou au contraire, de phases pluvieuses surabondantes.

Quant aux besoins en eau, ils varient surtout en fonction du degré et de la rapidité de couverture du sol nu au départ de la culture, par la végétation: ainsi, des variétés très précoces (croissance et développement accélérés) ou semées à des densités fortes, couvrent plus rapidement le sol que d'autres, et expriment des besoins hydriques plus importants. Ces besoins en eau décroissent aussi avec le vieillissement de la culture; or ce vieillissement peut coïncider avec une demande évaporative faible, au coeur de la saison des pluies, pour une variété très hâtive comme le mil de 75 jours, ou au contraire coïncider avec une demande évaporative de plus en plus élevée, en fin de saison des pluies, pour une variété de cycle long, comme un mil de 120 jours.

C'est pourquoi, là encore, il convient de ramener les besoins en eau à la demande évaporative (évaporation d'eau libre en bac normalisé classe A) et de calculer les coefficients $K = \frac{ETM}{Ev\ bac}$, tout au long du cycle. Nous avons donc fait celà, pour les trois sortes de mil testées et pour des périodes successives de 15 jours, ce qui donne le Tableau 4. Comme chaque type de mil a été testé au moins pendant 2 années successives, nous avons comparé les coefficients K obtenus et retenu une valeur moyenne caractéristique.

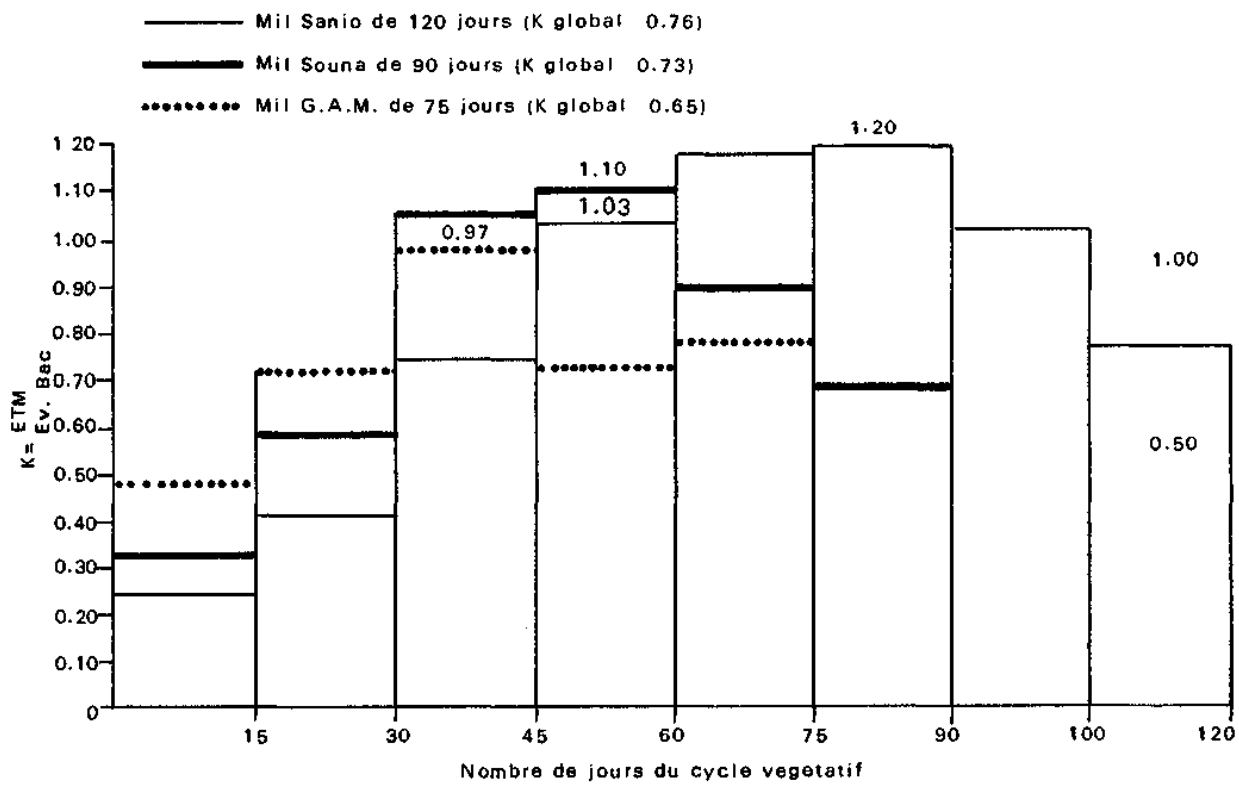
Le Graphique 2, dans lequel ne sont utilisées que les valeurs de K retenues, met très bien en évidence les différences entre les trois sortes de mil. On remarquera en particulier les valeurs maximales de K atteintes:

1,20 pour le mil Sanio; 1,10 pour le mil Souna; 0,97 pour le mil GAM.

De la même façon, nous avions vu dans le Tableau 1, que les coefficients K globaux étaient de l'ordre de 0,76 pour le mil Sanio; 0,73 pour le mil Souna et 0,65 pour le mil GAM. Il semble que ces deux faits soient liés à la taille respective de ces mils: les mils Sanio sont très hauts

Tableau 4. Evolution des coefficients $K = \frac{ETM}{Ev\ bac}$ au cours du cycle, pour des variétés de mils de 75 à 120 jours.

Période (jours)	Mil Sanio 120 jours			Mil Souna 90 jours			Mil GAM, nain 75 jours		
	1976	1977	Valeur retenue	1973	1974	Valeur retenue	1974	1975	Valeur retenue
0–15	0.15	0.30	0.23	0.26	0.38	0.32	0.44	0.49	0.47
15–30	0.35	0.44	0.40	0.49	0.66	0.58	0.61	0.80	0.71
0–30	0.25	0.37	0.31	0.38	0.52	0.45	0.53	0.65	0.59
30–45	0.77	0.70	0.74	1.09	1.01	1.05	0.84	1.10	0.97
45–60	1.07	0.99	1.03	1.26	0.94	1.10	0.79	0.65	0.72
30–60	0.92	0.84	0.88	1.18	0.98	1.08	0.82	0.88	0.85
60–75	1.12	1.24	1.18	0.98	0.82	0.90	0.75	0.80	0.77
75–90	1.24	1.15	1.20	0.72	0.65	0.69			
60–90	1.18	1.20	1.19	0.85	0.74	0.80			
90–105	1.09	0.94	1.02						
105–120	0.71	0.82	0.77						
90–120	0.90	0.88	0.89						



Graphique 2. Evolution des coefficients $K = \frac{ETM}{Er\ Bac}$ au cours du cycle de trois variétés de mil de 75, 90 et 120 jours.

(plus de 3,5 m), les mils Souna sont intermédiaires (2–2,5 m) et les mils nains ont autour d'1,0 de haut. De plus, alors que la surface d'un champ de mil Sanio est très irrégulière (en vagues), celles du mil Sanio et surtout du mil GAM sont beaucoup plus homogènes: tous ces facteurs font que les advections d'énergie sont certainement plus élevés pour le Sanio que pour les autres cultures et que les besoins en eau sont ainsi majorités. Il n'est cependant pas évident que les mêmes résultats soient trouvés en très grandes parcelles (>1 ha) où les advections d'énergie seraient probablement réduits. Ceci repose en fait le problème de l'échelle de la caractérisation agroclimatique: petite parcelle, champ ou zone écologique. Mais il se peut aussi que les différences trouvées, soient vraiment liées à la physiologie ou à l'architecture des plantes testées, ce qui reste à démontrer; la vérité se trouve peut-être entre ces diverses hypothèses.

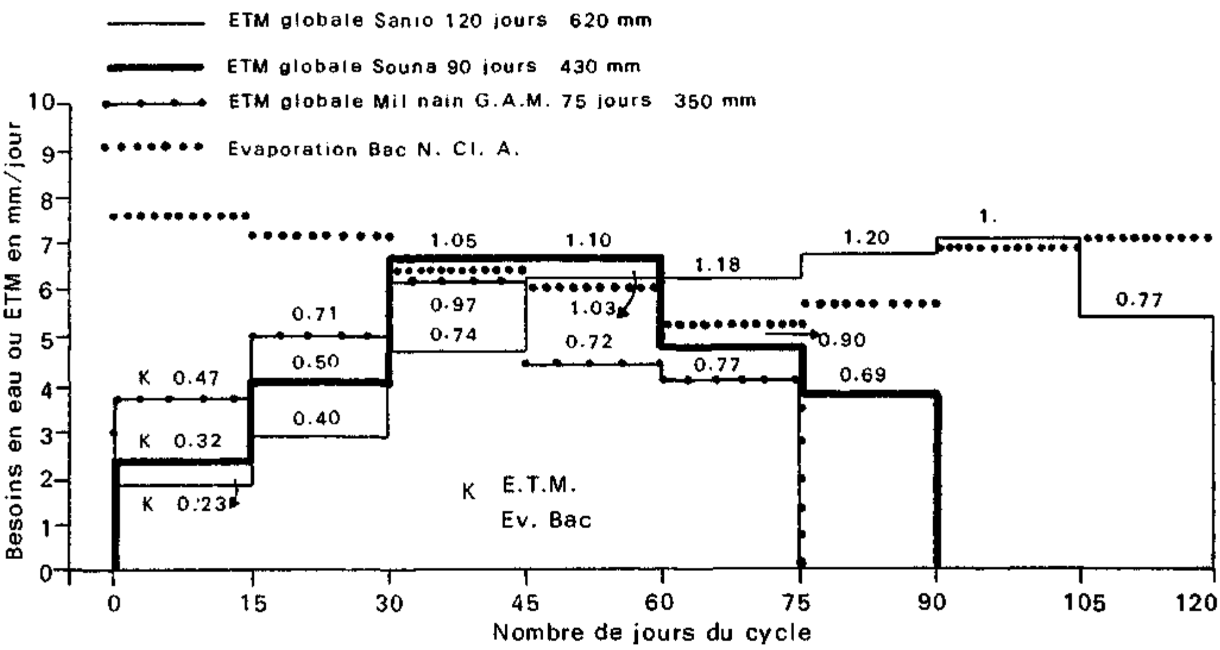
A partir des valeurs K retenues et de l'évaporation du bac normalisé classe A, par quinzaines de jours successives et moyennées sur la période 1972–1977, à compter de la date de démarrage de la culture, il devient possible de comparer valablement les trois variétés (Graphique 3). De cette comparaison ressortent très bien les besoins en eau supérieurs pour les variétés de cycle court, en début de culture, et pour les variétés de cycle plus long, en fin de campagne.

Généralisation des Résultats à l'Echelle du Sénégal

Méthode

On sait qu'au Sénégal, la demande évaporative varie au cours d'une même période, en allant du Nord vers le Sud et même de la côte vers l'intérieur des terres. Elle est élevée vers le Nord et plus faible vers le Sud; elle augmente en allant à l'intérieur du continent. Cette demande évaporative est bien sûr en liaison avec l'humidité de la zone, c'est-à-dire avec le facteur pluie, principal responsable de l'humidification.

La remontée du front intertropical, vers le Nord, amène des masses d'air humide; les pluies s'installent et humectent le sol. La végétation commence à couvrir le sol et l'évapotranspiration des cultures contribue, de même que les conditions caractéristiques de la saison des pluies (diminution des durées d'insolation et des températures, augmentation de l'humi-



Graphique 3. Besoins en eau comparés de trois variétés de mil, à Bambey, ramenés à une demande évaporative moyenne (1972–1977).

dité relative de l'air, réduction de la vitesse des *vents, etc...) à réduire la demande évapora*tive.

Des corrélations négatives entre les quantités de pluie reçues et l'évapotranspiration potentielle mesurée sur gazon (DANCETTE 1973), entre la pluie et l'évaporation potentielle d'eau libre en bac normalisé classe A (DANCETTE 1977), ont pu être établies et permettent de caractériser localement la demande évaporative pendant la saison des pluies. Ceci était essentiel pour nos travaux d'adaptation des cultures pluviales, basés sur la généralisation à l'ensemble du pays, de mesures de besoins en eau réalisées ponctuellement. On peut ainsi valoriser un réseau pluviométrique relativement dense et ancien, ce qui n'est pas le cas du réseau de mesure de l'évaporation.

En ce qui concerne les relations entre la pluviométrie et l'évaporation bac, elles sont mensuelles ou globales pour la durée de la saison des pluies, et du type:

Ev bac = A − BX − CY + DZ

où X est la pluviométrie du mois ou de la saison considérée

Y est la pluviométrie moyenne annuelle de la station (liaison avec la latitude)

Z est la continentalité, c'est-à-dire la distance séparant la côte océanique de la station (liaison avec la longitude surtout).

Ce type de relation est déterminé pour des mois de transition (début de saison des pluies) ou pour des mois de pleine saison des pluies, ou enfin pour toute une période de pluies possibles (juin à octobre compris); les coefficients de corrélation trouvés sont respectivement de 0,73; 0,78 et 0,86.

Il existe un genre de relation plus simple, à l'échelle des 5 mois de saison des pluies, de la forme:

Ev bac = 10,4 − 2,76 Ln P (r = 0,92)

où Ev est l'évaporation bac moyenne en mm/ *jour pour les 5 mois considérés*

et P est la pluviométrie moyenne par jour pendant la même durée.

A partir de ces relations, on peut établir le genre de carte suivant, pour caractériser localement la demande évaporative (traduite par l'évaporation en bac normalisé classe A), pendant la saison des pluies au Sénégal. Sur cette carte, sont chiffrées les évaporations moyennes en mm/jour (juin à octobre compris) et, entre parenthèses, un indice calculé par rapport à la station de Bambey, où nous avons mesuré les besoins en eau du mil (Graphique 4).

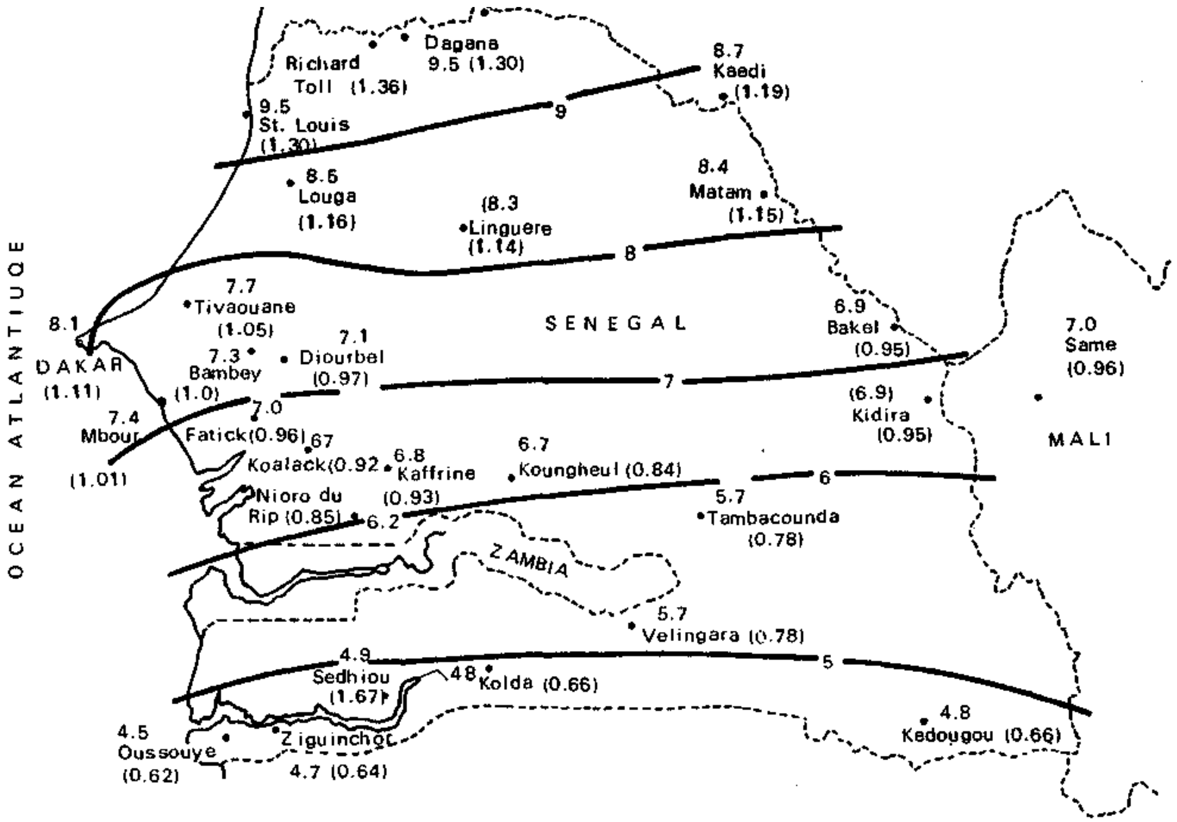
Critiques

Elles peuvent porter sur de nombreux points, entre autres:

- la relativité des données mensuelles dans ce domaine (la pluie peut tomber en début de mois, ou en fin de mois, sans être bien répartie au cours de ce mois; là pluie d'un mois donné peut influencer le mois suivant par le biais des réserves hydriques du sol, etc...);
- la durée globale de 5 mois retenue; selon que l'on retient ces 5 mois, ou la durée exacte entre la première pluie utile et la date de fin de saison des pluies utiles (dernière pluie + période d'utilisation des réserves hydriques du sol), ou un nombre de mois entiers bénéficiant vraiment de pluies notables, les relations restent très voisines et ne justifient pas à notre avis, de compliquer davantage les calculs.

  Le problème qui se pose de façon plus cruciale est de savoir *quelle période on veut ou doit retenir* pour caractériser cette demande évaporative. En 1973, pour la relation entre la pluie et l'ETP pendant la saison des pluies utile et la carte d'ETP alors esquissée, nous avions considéré une grande période (1931–1965); ce qui atténuait beaucoup le gradient de demande évaporative: 1,20 en gros à l'extrême Nord du pays et 0,80 à l'extrême Sud du Sénégal, par rapport à Bambey.

  Par contre, entre 1971 et 1976, période de mise en place et extension de notre réseau de bacs normalisés classe A, nous avons subi une période de sécheresse exceptionnelle. Nous n'avons pas osé généraliser à la période 1931–1976, notre relation entre la pluie et l'évaporation bac. Cette relation, en attendant confirmation sur une période plus longue de relevés d'évaporation et de pluie, est caractéristique d'années déficitaires en pluie et à demande évaporative anormalement élevée.



Graphique 4. Carte des variations de demande évaporative (mm/jour) au Sénégal pendant les mois d'hivernage (juin à octobre compris, 1971–1976).

Ainsi, la carte exprimant la demande évaporative et son gradient Nord-Sud, indique des indices par rapport à Bambey, compris cette fois entre 1,40 au Nord du pays et 0,65 au Sud. Cependant, à notre avis, il vaut mieux orienter nos travaux vers une adaptation des cultures aux conditions défavorables de ces dix dernières années, sachant qu'il n'en sera que plus facile de s'adapter à des conditions meilleures.

utilisation de la carte de demande évaporative et des indices calculés par rapport à Bambey

D'après cette carte, un mil de 120 jours qui aurait besoin en moyenne de 620 mm à Bambey, exigerait:

$620 \times 0{,}82 = 530$ mm à Nioro-du-Rip
et $620 \times 0{,}67 = 420$ mm à Séfa.

De même pour un mil de 75 jours qui exigerait 350 mm d'eau à Bambey, il faudrait:

$350 \times 1{,}16 = 410$ mm à Louga
et $350 \times 1{,}30 = 460$ mm vers Dagana.

Quelques Commentaires et Applications

Potentialités des Variétés de Mil Actuelles dans le Centre du Sénégal

A partir du Tableau 5, on peut constater que les meilleurs rendements grain sont obtenus actuellement avec le mil Souna de 90 jours (près de 3 t/ha). D'ores et déjà, les mils de 75 jours (GAM) en cours d'amélioration variétale permettent d'obtenir les mêmes rendements grain que le mil Sanio de 120 jours (en cours d'abandon total dans la région de Diourbel): ce dernier plafonne à 2 tout en consommant près de deux fois plus d'eau que le mil GAM.

Si on chiffre la valorisation de l'eau par le mil, en nombre de litres d'eau effectivement con-

Tableau 5. Consommation hydrique et rendements du mil.

Culture	Année	Pluviométrie (mm)	Traitement	Evapotranspiration (mm)	Rendements (kg/ha) Grain	Rendements (kg/ha) Paille	Quantité d'eau nécessaire (litres/kg) Grain sec	Quantité d'eau nécessaire (litres/kg) M.s. aérienne totale[a]	Taux de satisfaction des besoins en eau
Sanio	1976	399	Arrosé 215 mm	562 C.V.6%	2035 (7,5) C.V.7%[b]	13 950 (3,2) C.V. 11%	2986	337	100%
			Non arrosé	403 C.V.3%	1092 (7,4) C.V. 16%	10 478 (2,2) C.V. 10%	4045	334	72%
Sanio	1977	374	Arrosé 283 mm	628 C.V.4%	1623 (3,5)[c] C.V. 8%	14 425 (7,5) C.V.4%	4010	387	100%
			Non arrosé	397 C.V. 4%	153 (3,5) C.V. 71%	11 172 (8,5) C.V.14%	26 890	364	63%
Souna	1973	400	Arrosé 68 mm	417 C.V.3%	2690(7,8) C.V.5%	6680 (4,3) C.V. 7%	1681	412	100%
			Non arrosé	378 C.V.3%	2770 (7,8) C.V. 3%	6240 (4,3) C.V. 6%	1443	383	91%
Souna	1974	492	Arrosé 73 mm	416 C.V.7%	2948 (5,4) C.V. 3%	5760 (5,2) C.V. 4%	1492	426	100%
			Non arrosé	415 C.V.8%	2951 (5,2) C.V. 2%	5590 (5,1) C.V. 8%	1483	434	100%
Mil G.A.M	1974[d]	447	Arrosé 51 mm	320	2151 (9,0)	5943 (8,4)	1635	342	100%
			Non arrosé	324	2288 (8,3)	5780 (8,4)	1544	350	100%
Mil G.A.M	1975	510	Non *arrosé* (Pluies suffisantes)	327 C.V.6%	1721 (9,2) *C.V. 12%*	5652 (10,2) *C.V. 10%*	2093	414	100%

a. La matière sèche aérienne comprend : paille, grain, enveloppes et rachis.
b. A côté des rendements sont notées entre parenthèses les humidités et en dessous, les coefficients de variation C.V.
c. 3 parcelles sur 4 ont été gardées seulement.
d. En 1974, on est passé sur l'essai mil G.A.M., de 2 points de mesure à 5 en fin de campagne d'où l'impossibilité de faire une analyse statistique.

sommés par la culture et nécessaires pour fabriquer un kilo de grain sec, elle est peu différente entre les mils Souna et GAM.; par contre elle est beaucoup plus mauvaise pour le mil Sanio (3.000–4.000 litres/kg de grain au lieu de 1.500–1.600 litres pour les autres mils).

En ce qui concerne la paille, il faut reconnaître les potentialités de production élevées du mil Sanio: autour de 14 t/ha, soit plus du double des mils Souna et GAM. Pour fabriquer un kilo de paille, il faut en moyenne:

- 440 litres d'eau pour le mil Sanio irrigué (moyenne entre 1976 et 1977)
- 616 litres d'eau pour le mil GAM (moyenne entre 1974 et 1975)
- 707 litres d'eau pour le mil Souna irrigué (moyenne entre 1973 et 1974).

On remarquera que le mil nain de 75 jours ne fait rien perdre par rapport au mil Souna, en production de paille: les rendements paille sont très voisins, mais bien sûr, ils sont obtenus en 75 jours au lieu de 90, ce qui est appréciable.

On ne peut pas actuellement négliger cet aspect "production de paille," compte tenu de son utilisation croissante pour l'alimentation du bétail, la fabrication du fumier et l'habitat (toitures, clôtures, combustibles, etc . . .).

Sans vouloir revenir au mil Sanio de 120 jours, à proscrire pour sa faible potentialité en grain et pour sa consommation hydrique excessive, on peut se demander si l'abandon du mil Sanio, dans la région de Diourbel, n'a pas contribué à accroitre le déficit en paille des exploitations (un des freins actuels au développement de l'élevage fixé); il en est de même lorsqu'on passe des arachides de 120 jours à celles de 90 jours. La "sécurisation" des rendements en grain est peu compatible avec des productions de paille élevées.

Influence des Stress Hydriques sur la Production de Mil

Les mils Souna et GAM, très bien adaptés dans l'ensemble aux conditions hydriques de la zone de Bambey, n'ont pas été vraiment stressés au cours de ces années d'expérimentation, pourtant déficitaires en pluie. Ainsi, en 1973, le mil Souna non arrosé a vu ses besoins en eau satisfaits à 91% et ses rendements en grain et paille, très peu différents de ceux du mil arrosé en complément. Pour les autres années, l'irrigation d'appoint n'a rien apporté de plus, tant pour le mil Souna que pour le mil GAM. T.M. DUC (1977) sur la ferme irriguée de Bambey a eu des résultats assez voisins en ce qui concerne les mils Souna pendant la saison des pluies: l'irrigation d'appoint est surtout valorisée en remontant plus au Nord. Par ailleurs, il existe d'autres moyens que l'irrigation pour "sécuriser" la production de mil dans le Centre du pays: ce sont en particulier les techniques de dry farming, avec un report de réserves hydriques dans le sol, d'une année sur l'autre (CHOPART et NICOU 1976).

Par contre, pour le mil Sanio, très mal adapté à ces années déficitaires (470 mm de pluie à Bambey, au cours des 10 dernières années, au lieu de 640 pour la période 1921–1976) les différences entre parcelles irriguées et non, sont très fortes. Un mil Sanio dont les besoins en eau ont été satisfaits globalement à 72% en 1976, voit son rendement grain chuter de 46% et son rendement paille de 25%. Pour un mil Sanio dont les besoins ont été couverts à 63% en 1977, le rendement grain tombe de 1.623 à 153 kg/ha, soit une chute de 91% ! Le rendement paille est moins affecté, puisqu'il ne chute que de 23%.

En regardant de plus près ce qui se passe au moment de la floraison qui a eu lieu pour le mil irrigué:

- le 2 octobre (82ème jour de cycle) en 1976, à la mi-épiaison
- le 7 octobre (92éme jour de cycle) en 1977 (floraison plus étalée)

On s'apercoit que le stress hydrique pendant les 20 jours encadrant ces dates moyennes, peut être chiffré à:

$$\frac{(ETM - ETR)\,\%}{ETM} = \frac{5,8 - 4,7}{5,8} = 20\% \text{ en } 1976,$$

ce qui correspond à une chute de rendement grain de 46 % et:

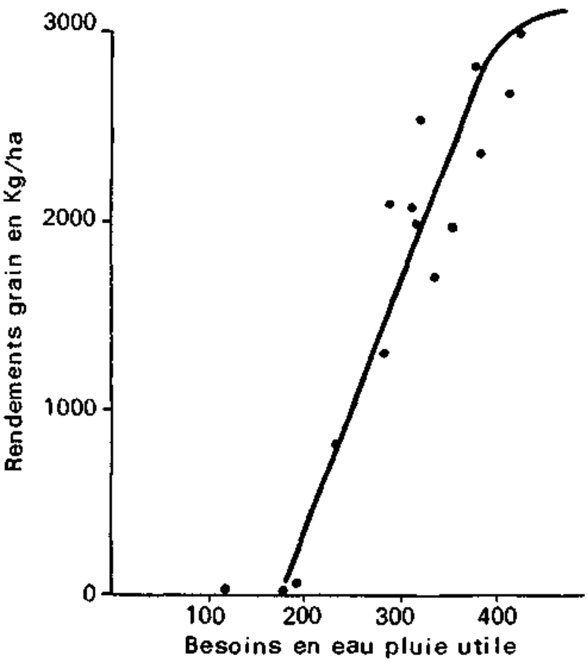
$$\frac{6,5 - 2,9}{6,5}\,\% = 55\% \text{ en } 1977, \text{ qui correspon-}$$

dent à une réduction de rendement grain de 91 %.

Plus que le stress global sur toute la durée du cycle, il convient donc de surveiller particulièrement ce qui se passe au moment de l'épiaison.

En l'absence de véritable essai de courbe de réponse à l'eau, pendant la saison des pluies, ce qui implique des toitures mobiles ou des serres parfaitement climatisées, nous avons essayé d'approcher cette courbe, en utilisant les divers essais agronomiques de Bambey et des autres stations. Soit les consommations hydriques étaient effectivement mesurées par bilan hydrique *in situ*, soit elles étaient assimilées à la pluie utile relevée, lorsque cette dernière était relativement bien répartie (et donc stockée à une profondeur du sol prospectable par les racines) et nettement inférieure aux besoins. Ceci nous a permis d'obtenir, à ce premier stade d'investigation, la courbe de réponse à l'eau du mil souna de 90 jours, pour la zone centrale (Thiès-Bambey Diourbel), en très bonnes conditions de technicité (Graphique 5).

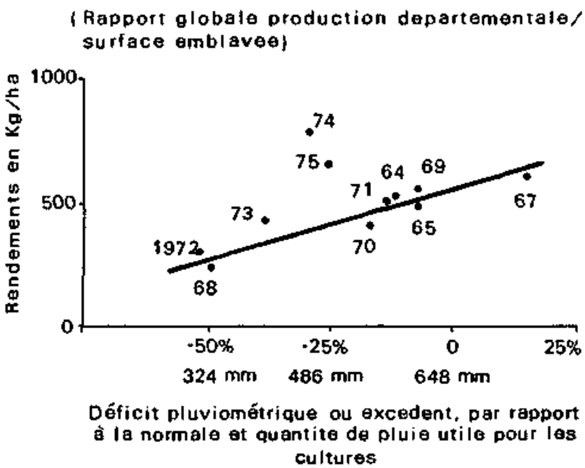
Nous essayerons prochainement de faire le même travail, pour les mils de 75 et de 120 jours, non seulement en conditions de station, mais aussi en conditions paysannes. Ce genre d'enquête permet entre autres informations, de mieux expliquer la production, et d'apprécier plus objectivement l'impact des efforts de vulgarisation, en dissociant les facteurs techniques et les facteurs climatiques par exemple. Le Graphique 6 est une première tentative dans ce sens, bien que très critiquable: les mils de 90 et 120 jours et les sorghos n'étant pas différenciés et l'estimation des rendements étant sujette à caution. Quelle que soit la valeur exacte des chiffres, on retrouve toutefois une logique dans les tendances discernées: l'effet des sécheresses exceptionnelles de 1968 (record de sécheresse sur 50 ans), 1972 et 1973, et peut-être une tendance qui demande à être confirmée, dans l'augmentation des rendements de mil constatée en 1974 et 1975. Les raisons qui peuvent être invoquées sont les suivantes: abandon quasi-total des mils de 120 jours et des sorghos dans la zone considérée; changement de méthode d'estimation au niveau de la DGPA; progrès technique (démariage, fertilisation, etc...). Il est utile, aussi bien pour la recherche que pour la vulgarisation, de mieux comprendre les mécanismes de la production, afin de mieux orienter les interventions ultérieures.



Graphique 5. Courbe de réponse à l'eau des mils Souna (90 jours) en très bonnes conditions de travail, fumure et entretien (Stations et Papem, ISRA, Centre - Nord).

Cartes d'Adaptation du Mil aux Conditions Pluviales

Nous n'insisterons pas beaucoup sur ce point qui a fait l'objet d'une communication au Com-



Graphique 6. Evolution des rendements de mil et sorgho en conditions paysannes dans le département de Bambey (Evaluation D.G.P.A).

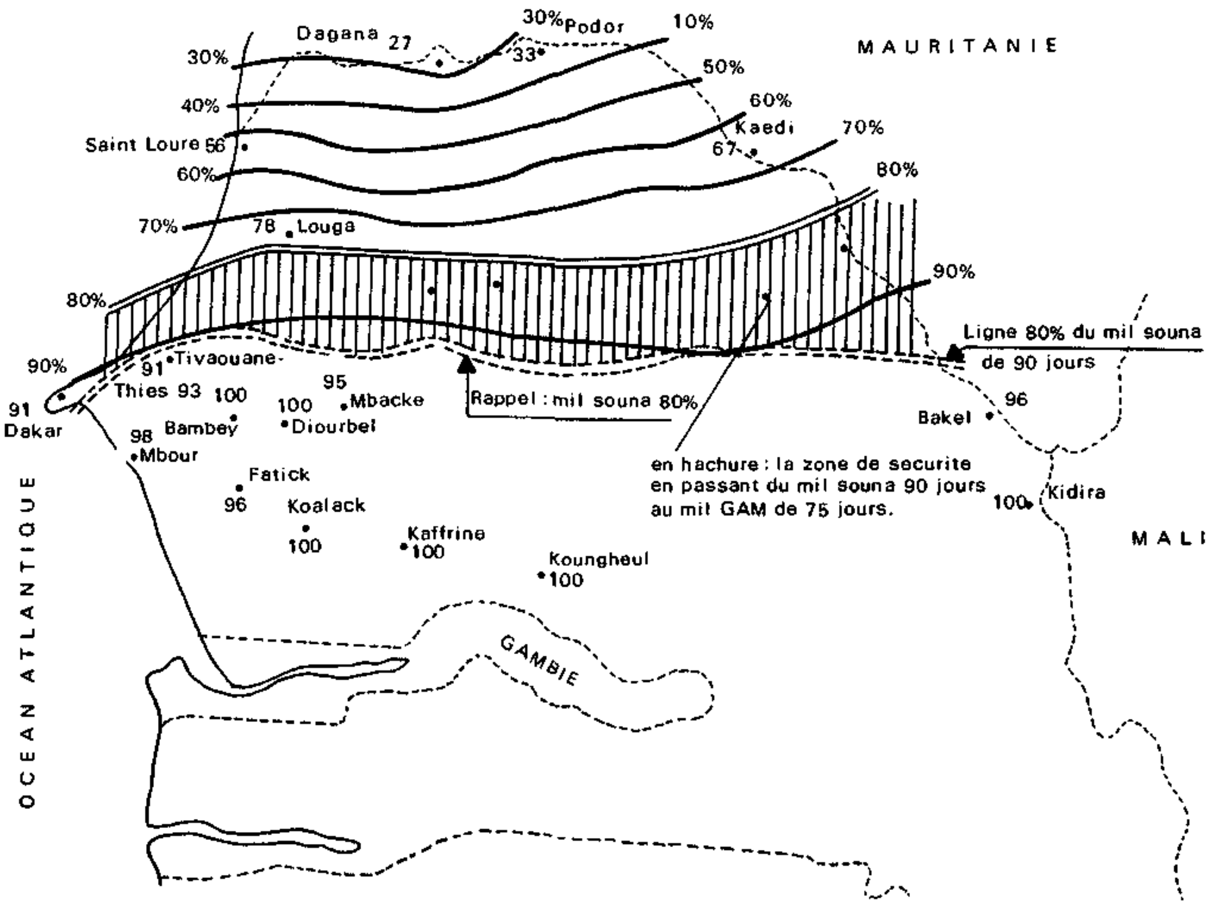
ité Consultatif AIEA de 1975 à Bambey (DANCETTE 1975). Cette note concernait les mils à cycle court de 75 et 90 jours, dans la moitié Nord du Sénégal. Il faudrait étendre ce travail à l'ensemble du territoire, en considérant en plus les mils Sanio de 120 jours, pour le Centre et le Sud du Pays.

Nous rappellerons qu'en 1975, le gradient de demande évaporative avait été chiffré à partir d'une carte d'ETP établie pour la période 1931–1965 (corrélation pluie-ETP); les résultats seraient encore plus pessimistes si on considérait la demande évaporative des 10 derniéres annèes, à partir des corrélations pluie-évaporation bac.

La méthode est basée sur l'étude de la saison des pluies utiles pour une culture de mil semée en sec, et sur la confrontation entre la pluie *reçue et stockée dans le sol (á concurrence* de 100 mm) et les besoins en eau du mil estimés à±10%, au cours de la culture. Il faut donc tenir compte à la fois de la longueur de la saison des pluies utiles et de la satisfaction des besoins en eau, pour savoir si, rétrospectivement, chaque année analysée dans une station, avait été favorable ou non sur le plan hydrique. Ceci nécessite d'analyser en détail une quarantaine d'années par station et d'étudier toutes les stations disposant d'une série d'observations relativement longue et complète, et par ailleurs bien réparties sur le territoire. La carte ci-jointe (Graphique 7) donne une idée des renseignements que l'on peut obtenir. La partie hâchurée représente la zone de sécurité accrue (80% de chances de réussite et plus) que l'on peut gagner en passant d'une variété de 90 jours (Souna) à une variété de 75 jours (mil nain GAM).

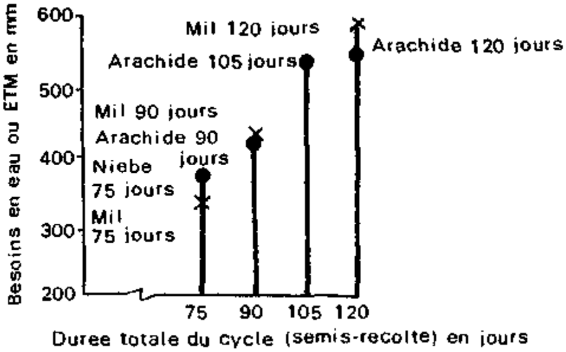
Suivi de la Campagne Agricole et Explication de la Production

Nous avons tenté en 1977 (DANCETTE 1977), un



Graphique 7. Lignes d'égale probabilité pour que les conditions hydriques soient favorables à une culture de mil G.A.M. de 75 jo urs.

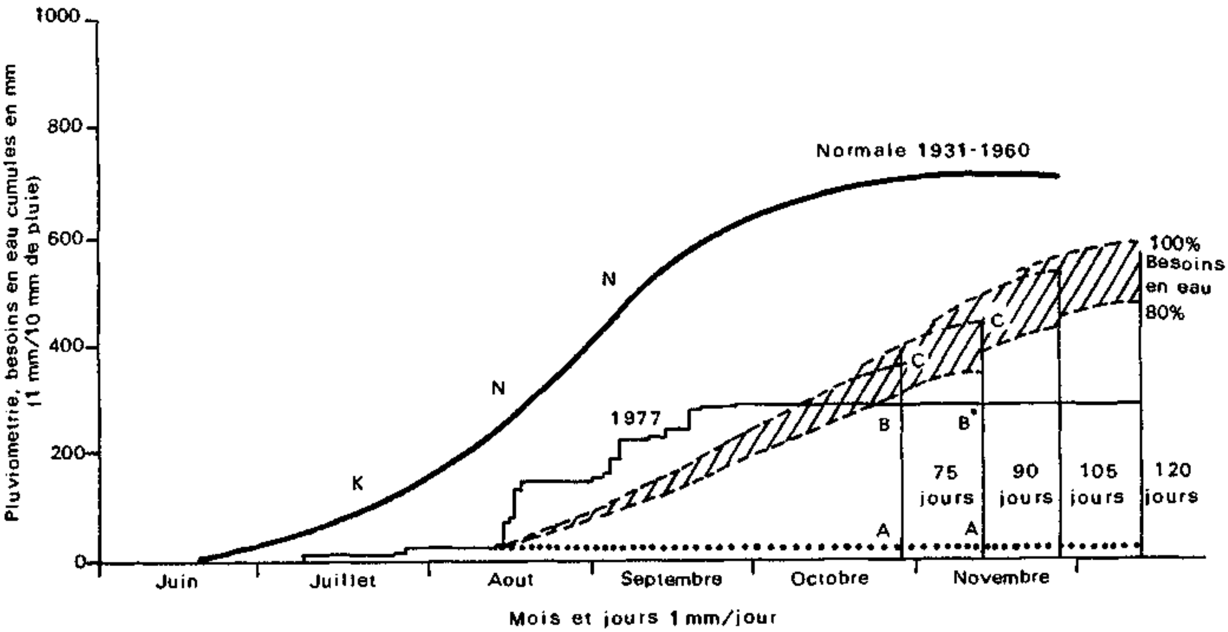
suivi très général de la campagne agricole, axé essentiellement sur les cultures de mil, arachide et niébé, dont les besoins en eau, sont en fin de compte assez voisins, à longueur de cycle égale. Pour ces cultures, les besoins en eau sont directement proportionnels à la longueur du cycle végétatif (Graphique 8). Aussi est-il possible graphiquement de porter les courbes cumulées de besoins en eau et de pluviométrie, à partir du jour de première pluie utile (Graphique 9). Cette première pluie utile est celle qui permet à la culture de mil semée en sol sec, de commencer à pousser. L'idéal serait de pouvoir éventuellement translater cette courbe des besoins en eau, le long de l'axe des abscisses (jours), et aussi de la décaler le long de l'axe des ordonnées (mm), en cas de resemis d'une part ou de retard au semis tout simplement.



Graphique 8. Les besoins en eau des cultures au Sénégal sont proportionnels à la longueur du cycle de végétation.

En effet, dans ces cas, soit la culture commence avec un stock d'eau initial que l'on peut estimer, soit toute la pluie a été perdue (évaporation) et il faut faire partir la courbe de besoins en eau, du niveau de la pluviométrie accumulée atteinte (cas de Thiès en 1977). Enfin, dans certains cas exceptionnels (stations de recherche), il peut exister un stock hydrique initial dû à des techniques de dry farming (labour de fin de cycle par exemple): dans ce cas, il conviendrait d'en tenir compte, en abaissant par rapport à la simple pluviométrie, le point de départ de la courbe de besoins en eau.

Pour le suivi de la campagne de mil proprement dite, il suffirait de reprendre exactement les résultats de besoins en eau spécifiques exposés plus haut et de leur affecter par station, un indice tenant compte du gradient de demande évaporative. On peut voir ainsi très facilement, quelles sont les périodes de stress



Graphique 9. Suivi de la saison des pluies 1977 (Thies-Météo.). Trois resemis de mil en sec; Pluie de semis de 14 Août (52 mm); Date moyenne dernière pluie = 5 Octobre.

et même avoir une idée de l'intensité de ce stress et de ses effets possibles sur les rendements (en s'aidant aussi des courbes de réponse à l'eau). Dans le cas de Thiès, extrait des 25 autres cas étudiés en 1977, on voit que le début de la culture a été exceptionnellement tardif, et la pluviométrie très faible. A supposer qu'il y ait eu un ruissellement et une percolation négligeables, et que toute la pluie ait pu être stockée dans le sol et utilisée par la culture, on peut se rendre compte que seules les variétés de 75 jours avaient quelque chance de réussite (besoins en eau satisfaits au mieux à 76%); les mils de 90 jours avaient déjà commencé à souffrir au moment de l'épiaison (vers le 60ème jour) et leurs besoins hydriques n'ont

été couverts globalement qu'à 62% ($\frac{A\ 'B'}{A\ 'C'}$ sur le Graphique 9).

Conclusion

La mesure des besoins en eau est un préalable à tout travail portant sur l'adaptation des cultures à un milieu pédoclimatique donné. Ainsi, pour le mil, on sait maintenant assez bien quelles sont ses exigeances hydriques, à un haut niveau de technicité. On sait moins ce qu'exigerait un mil médiocrement cultivé et mal alimenté sur le plan minéral. Cependant, il est normal que la recherche vise à l'obtention de hauts rendements et donc à l'adaptation de plantes relativement plus exigeante en eau que des plantes chétives. Par ailleurs, nous avons vu que la production de paille devait, elle aussi, être considérée avec intérêt, au niveau d'une exploitation intégrant l'élevage et d'autres besoins.

Ces diverses raisons font que plus qu'autrefois, (on disposait alors de variétés médiocres, mais peut-être plus plastiques), il faut être très strict en ce qui concerne les critères de sélection variétale et la délimitation géographique, sur des bases pédo-pluviométriques entres autres, des aires de vulgarisation des principales variétés. On peut dire qu'au Sénégal, c'est la démarche qui a été adoptée par le Groupe d'amélioration des mils (GAM), dont les travaux de sélection et de création variétales sont basés sur une concertation permanente avec les agronomes et les agro-économistes. Ces derniers peuvent préciser ce que veulent vraiment les cultivateurs, comment ils utilisent les produits et sous-produits de culture et à quelles contraintes ils sont soumis (temps, matériel, marché, etc . . .). Quant aux agronomes, ils peuvent préciser comment ces diverses contraintes peuvent être levées (pluviométrie, travail du sol, fumure et matière organique) et quelle sorte de matériel végétal serait pour eux la plus commode afin de résoudre les divers problèmes agronomiques.

Sélectionneurs et physiologistes peuvent ainsi tendre leurs efforts vers des objectifs précis et répondant exactement aux besoins du développement, même si ces besoins ne sont pas toujours définis de façon aussi claire qu'il le faudrait, ou s'ils évoluent trop rapidement. Ainsi, le grand développement de l'élevage fixé et de l'embouche, semble incompatible avec les labours d'enfouissement des pailles de mil, autrefois préconisés. Il est nécessaire en revanche de préserver la fertilité des sols, par des apports de fumier dont les modalités de fabrication et d'épandage demandent encore à être étudiées.

Tout ceci demande beaucoup de vigilance et de concertation et suppose des équipes pluridisciplinaires importantes et mobilisables pour des opérations planifiées, précises et régionalisées, comme le serait par exemple: l'augmentation de la production de mil, en vue d'assurer l'autosuffisance vivrière, dans une zone écologique donnée qui pourrait recouvrir une ou plusieurs régions administratives.

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Appendix II

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