WATER MANAGEMENT AND CROP PRODUCTION

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A REVIEW OF RESEARCH AT ICRISAT

FARMING SYSTEMS RESEARCH PROGRAM
ICRISAT

IRAT-ICRISAT WORKSHOP ON WATER MANAGEMENT AND CROP PRODUCTION
MONTPELLIER, FRANCE
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PREFACE

The Farming Systems Research Program (FSRP) at ICRISAT which was established in 1972, aims at developing farming systems to increase and stabilize agricultural production through better use of natural and human resources in the seasonally dry, semi-arid tropics (SAT). Water is the major constraint to increased and stabilized agricultural production in the Semi-Arid Tropics and has received the major emphasis in our FSRP. Agroclimatology, Land and Water Management, Environmental Physics, and Cropping Systems subprograms in the FSRP have evaluated several aspects of the role of water in crop production that cover rainfall climatology, climatic water balance, profile water dynamics, crop response to available water, water requirements, watershed management, and simulation modeling.

IRAT, the Institute for Tropical Crops Research (Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres), with its headquarters located at Montpellier in France, has been involved in water management and crop production research in Africa for many decades. Their research results provide valuable clues to management of water in the harsh environment of Africa. We at ICRISAT, with our global mandate for improving food production in the semi-arid Africa, have been following research at IRAT with considerable interest. It is opportune that now a workshop will be held at Montpellier to review the research on water management and crop production conducted at ICRISAT and IRAT. I am sure that this workshop will provide an effective forum for exchanging ideas and research results, and for evolving a future course of action whereby the two institutes can work together to achieve the aim of improved water management for increased crop yields.

In this publication **six** papers reviewing several aspects of research on water management and crop production conducted at ICRISAT over the past eight years are presented. These papers should provide an insight into the philosophy of the interdisciplinary research which is vital to the success of any farming systems research program. I wish the workshop all success.

Hyderabad

30 April 1982

J.C. Davies
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FARMING SYSTEMS RESEARCH AT ICRISAT
GOALS AND OBJECTIVES

The farming systems research at ICRISAT commenced in 1973. The goal of the Farming Systems Research Program (FSRP) at ICRISAT is consistently higher agricultural production in the seasonally dry tropics, especially for small farmers of limited means. Because the applicability of food production technology varies with the agroclimatic region, our research efforts focus on the development of principles, concepts, and methodologies that are transferable and have broad application. Therefore the FSRP aims to:

- describe and classify the agronomically relevant features of the soil and climatic resources of the SAT.
- identify the physical and biological processes that largely determine crop performance in the various agroclimates of the SAT, and establish basic principles that describe these processes.
- develop production practices and systems of farming that will result in improved, stable food production by optimum utilization of the SAT's natural resources.
- determine regional research priorities by execution of simulation and modeling studies based on climatic, soil, and cropping systems data.

This research is conducted at ICRISAT Center near Hyderabad, at several locations[1] in West Africa, and in farmers' fields in India and other SAT countries. Specific factors influencing crop yields are studied within the relevant subprograms of FSRP, but interactions among several of these factors often require interdisciplinary investigations with several subprograms in ICRISAT and with scientists from outside organizations. Alternative practices and systems of production developed from this research are initially tested in operational research at ICRISAT; those that appear promising are then evaluated on research stations and farmers' fields in the collaborative Village Level Studies in association with the Economics Program.

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[1] Particularly in Mali, Upper Volta and at ICRISAT Sahelian Center, Niamey, Niger.

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STUDIES ON RAINFALL CLIMATOLOGY, EVAPORATIVE DEMAND AND CLIMATIC WATER BALANCE CONDUCTED AT ICRISAT[1]

SM Virmani and MVK Sivakumar[2]

SUMMARY

Variations in the timing and amount of precipitation are generally the key factors influencing the agricultural potentialities of the Semi-Arid Tropical (SAT) regions. Analyses based on the average monthly, seasonal and annual rainfall to assess the moisture availability to crops is often inadequate because of the relatively high evapotranspirational demand during most of the growing season. Methodologies for assessing moisture availability to crops have been discussed. Use of probabilities of rainfall in relation to potential evapotranspiration and of the length of the dependable rainfall period enables comparison of diverse locations. Water balance techniques to examine soil-moisture availability and methodologies for choice of suitable crops/cultivars at selected locations have been discussed. The relevance of such agroclimatic analysis in transfer of farming systems technology is discussed.

1. INTRODUCTION

The dry tropical regions depend primarily on agriculture; the present low income levels are caused by low and unstable agricultural production. The distinctive characteristics of the tropical environment has a major influence on the distribution of natural endowments: soils, rainfall and climate. These areas are well supplied with radiant energy, however, due to the sunlight regime, temperatures and orographic influences, a variety of rainfall patterns are produced. Variations in the timing and amount of precipitation are generally the key factors influencing agricultural production possibilities.

The effect of differences in rainfall on the availability of moisture in tropical agriculture is especially great because of the rapid evaporation and transpiration by plants. As a result of consistently high temperatures during the year, the rate of evaporation is intense. The agricultural value of rainfall varies with the climatic

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[1] Paper for presentation at the IRAT-ICRISAT Workshop on Water Management and Crop Production, Montpellier, France, 3-6 May 1982.

[2] Principal Agroclimatologist and Leader, and Principal Agroclimatologist respectively, Farming Systems Research Program.

factors that influence the return of moisture to the air by evapotranspiration. Since plants meet almost all the water requirements from the root rhizosphere, water retention and release characteristics of the soils are important. Therefore, in determining the agricultural potentialities of any semi-arid area, a quantification of the rainfall (timing, amount and durations), soil (intake, storage and release) ane evapotranspiration characteristics is of fundamental importance. Given the variability of the semi-arid tropical environment, such a quantification also contributes substantially in delineating the potentially most rewarding areas for agricultural research.

2. THE SEMI-ARID TROPICS

ICRISAT has accepted the classification of climates based on thermal and hygric regimes proposed by Troll (1965). The emphasis in this classification is on the duration of dry and humid months rather than on an assignment of climatic boundaries based on annual values of precipitation, temperature, and humidity. According to Troll, the following climatic values proves satisfactory to explain the vegetation zones of tropical Africa and south America.

Humid months	General vegetation
12 to 9.5	Tropical rainforest and transitional forest
9.5 to 7	Humid savannah
7 to 4.5	Dry savannah (wet-dry semi-arid tropics)
4.5 to 2	Thorn savannah (dry semi-arid tropics)
2 to 1	Semi-desert (arid)
1 to 0	Desert (arid)

The approach used for defining humid months is simple: a month having a mean rainfall exceeding the mean potential evapotranspiration (PE) is termed as humid month. These data are available from national meteorological services. The classification proposed by Troll has been adopted by ICRISAT for defining the geographical extent of the semi-arid tropics (Fig. 1).

We have also used the method of Hargreaves (1975) for understanding the agricultural climate of the West African region. This method helps in evaluating moisture adequacies during the rainy season in three dry climates. Hargreaves developed a 'moisture availability index' (MAI) which is a measure of the adequacy of precipitation in supplying crop water needs. MAI is a ratio of PD/PE, where PE is the mean potential evapotranspiration. Computation of dependable precipitation (PD), requires the calculation of the amount of rainfall that could be received on specified probabilities. For most cases PD was defined at the 75% probability level. Areas with 3 or 4 consecutive months with an MAI of more than 0.33 are defined as semi-arid. Hargreaves further hypothesized that such areas are suitable for the production of crops requiring a 3- to 4-month growing period.

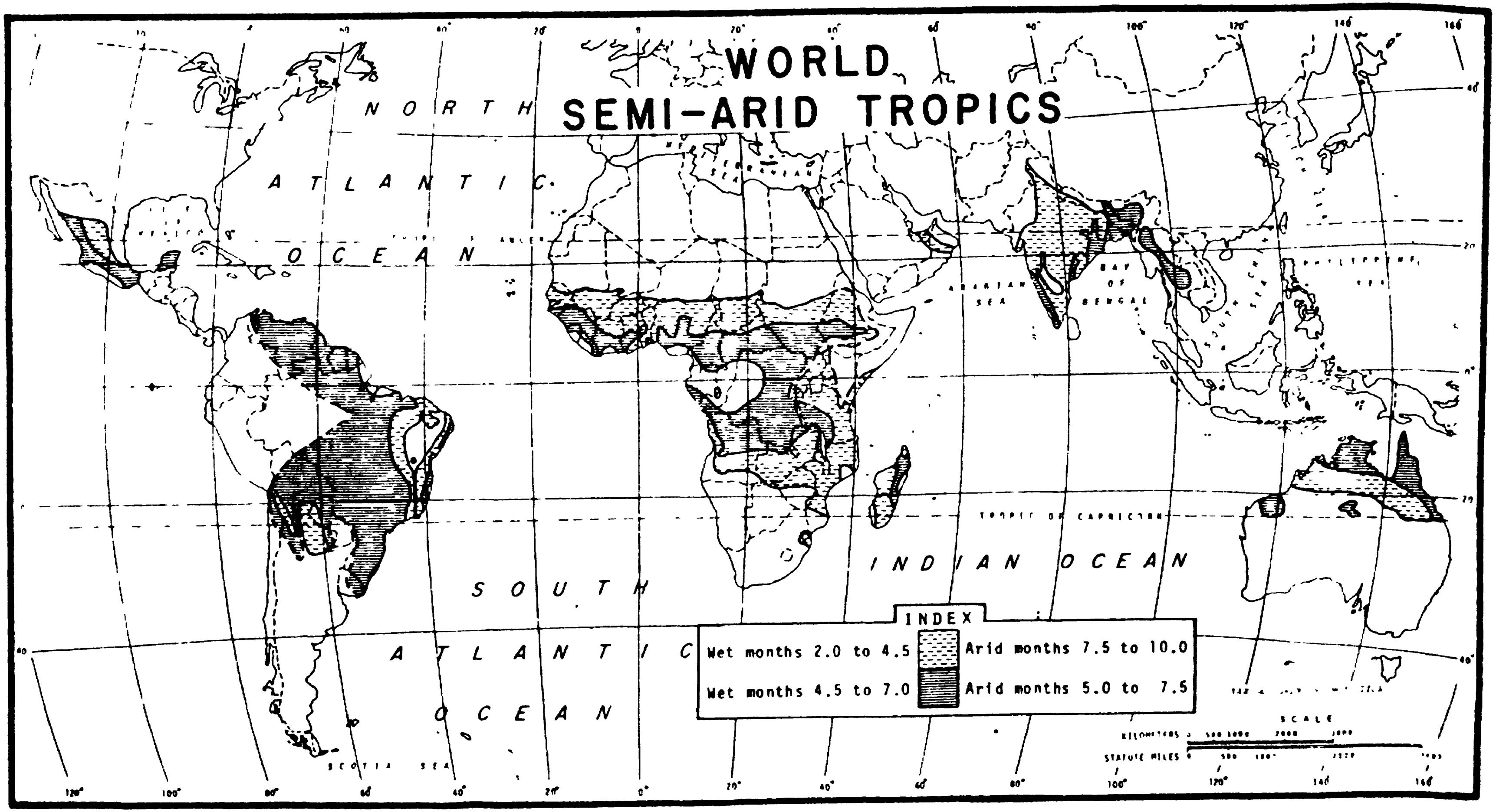

Figure 1. Semi-Arid Tropics of the World.

Calculations of precipitation probabilities require long-term rainfall records and are based on the choice of a suitable mathematical function that appropriately describes the distribution of rainfall in a particular climatic zone. These requisites impose a serious restriction on the universality of use of MAI in climatic classification systems.

The classification systems of Hargreaves and Troll are somewhat unique because average annual amounts of rainfall are not critical to these systems. This represents a strength because the annual average rainfall indeed says little about the agricultural potential in the dry tropics. It should be remembered that the number of months used in the classification criteria do not describe the entire rainy season; rather, they represent the core of the rainy period, which builds up to and drops from those key months. This is another strength of the 2 classification systems, for there is a direct correlation between the overall effectiveness of the rainy season and the number of months with precipitation equal to or more than potential evapotranspiration (or PD/PE > 0.33).

a) Characteristics of SAT Environments

The semi-arid tropics are characterized by a high climatic water demand. The mean annual temperature is $>18^{o}$C and rainfall exceeds evapotranspiration for 2-4.5 months in the dry semi-arid tropics and 4.5-7 months in the wet/dry semi-arid tropics. High rates of evaporation coupled with the characteristics of tropical rainfall pose particular problems. In many areas rainfall is markedly seasonal in character, greatly limiting water availability at certain times of the year. These temporal variations have a marked influence on water availability and hence on crop growth and development. Apart from the temporal variations, spatial variations in rainfall make the regional crop planning a difficult proposition.

i) Temporal variations in rainfall: SAT areas exhibit considerable variability from season to season and year to year. For example, the mean annual rainfall at Hyderabad is highly erratic and the data of the last 10 seasons presented in Table 1 show that the rainfall could vary from as much as 354 mm in 1972 to as high as 1172 mm in 1981. The variability is true not only annually but also seasonally. The rainfall distribution shows that seasonal rainfall is erratically distributed. For example in 1975, September was the wettest month whereas in 1977, September was the driest month. In 1978, August received the highest amount of rainfall whereas in 1972 August month was the driest.

ii) Spatial variation in rainfall and potential evapotranspiration: In order to characterize the spatial variation in the climatic environment of SAT areas, four locations: Bomako, Niamey, Dakar, and Hyderabad have been chosen. Some generalized characteristics of these locations are presented in Table 2. Figure 2 depicts the spatial variation in the rainfall and PE characteristics of the SAT environment. Bamako appears to be the most favourable with almost four months in a year when water supply could meet the potential requirement. Dakar is at the other end of the picture with only two months when the rainfall could satisfy the potential demand for water. Niamey also presents a similar situation. Hyderabad is intermediate between the two with three months in a year that meet the water demand-supply situation.

Table 1. Monthly rainfall received at ICRISAT Center from 1972 to 1981 and normal rainfall.

Month	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	Normal rainfall (mm)
JANUARY	0	0	0	35	0	0	17	0	0	16	2
FEBRUARY	0	0	0	0	0	0	21	41	4	0	10
MARCH	0	0	0	24	1	0	4	0	9	77	13
APRIL	0	0	15	0	91	8	56	3	7	3	23
MAY	8	3	15	2	22	36	15	78	18	2	30
JUNE	107	60	120	98	86	67	181	58	141	203	107
JULY	83	161	89	195	219	184	228	107	127	209	165
AUGUST	60	231	160	139	299	194	516	101	306	218	147
SEPTEMBER	63	69	186	422	74	40	82	345	153	287	163
OCTOBER	26	216	279	174	1	59	71	20	6	155	71
NOVEMBER	7	11	5	15	30	28	10	80	0	2	25
DECEMBER	0	1	0	0	0	2	1	0	2	0	5
TOTAL	354	752	869	1104	823	618	1202	833	773	1172	761

Table 2. Generalised characteristics of the four locations.

Location	Lat ° '	Long	Mean annual rainfall (mm)	Potential evapotranspiration (mm)
Bamako (Mali)	12 38 N	08 02 W	1099	1804
Niamey (Niger)	13 29 N	02 10 E	636	2057
Dakar (Senegal)	14 44 N	17 30 W	578	1825
Hyderabad (India)	17 27 N	78 28 E	761	1757

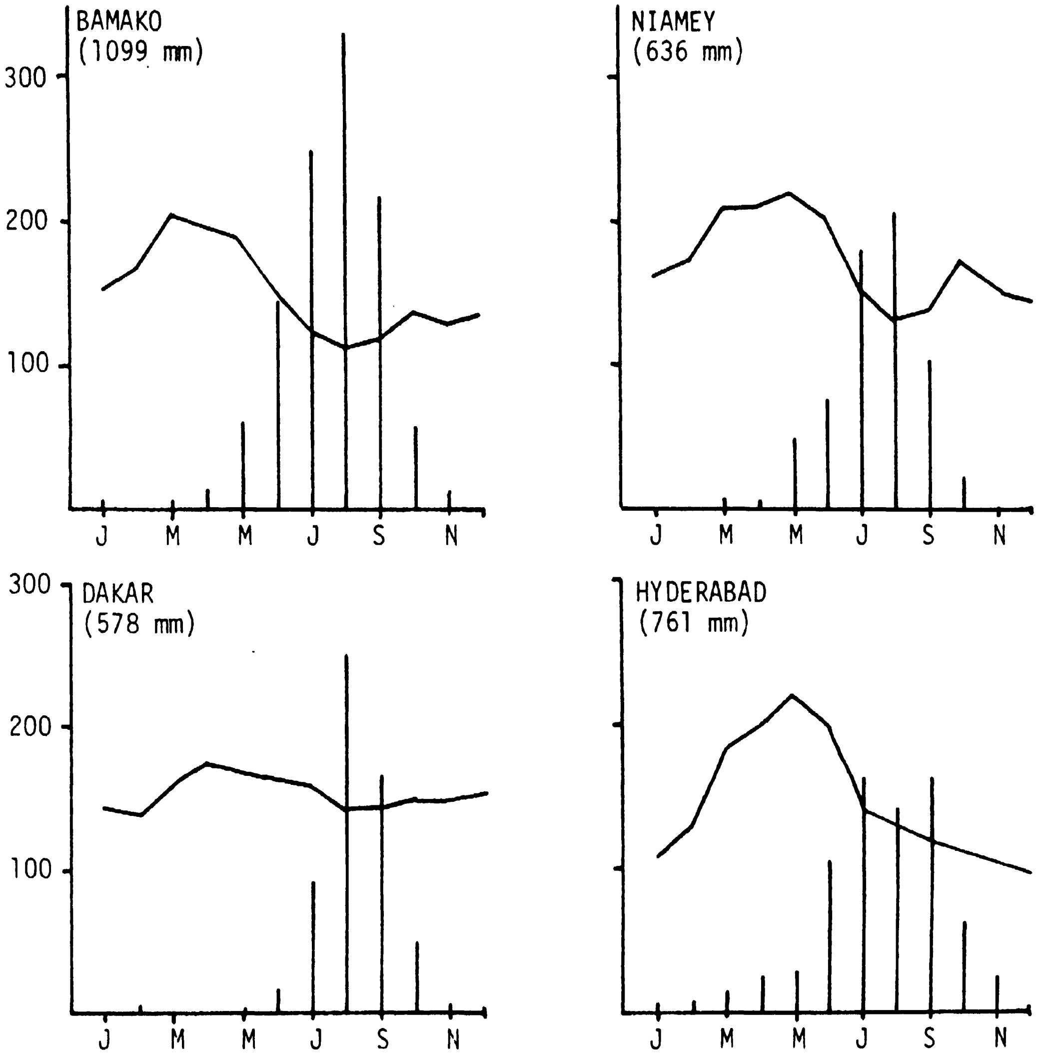

Figure 2. Rainfall (vertical bars) and potential evapotranspiration (
patterns at four selected locations in Asia and Africa (mea
annual RF in parenthesis).

The potential evapotranspiration curves in Figure 2 show some interesting patterns. At Hyderabad the curve shows typical low values beginning January peaking to high values around May-June and culminate in low PE values by November-December. This pattern is typical of the locations situated away from the equator, the high values of PE coinciding with 'high sun' and low values with the 'low sun' period. Bamako, Niamey and Dakar situated closer to the equator than Hyderabad however do not exhibit such large fluctuations. A good example is the pattern shown by Dakar. Bamako shows a sudden dip during July-September mainly because of cloudy skies and rain. The PE values are low on those days which have some amount of rainfall.

Monthly variations in the mean daily maximum and minimum temperatures at the six locations are shown in Table 3. Again low values of PE show a good correlation with the low values of daily maximum and daily minimum temperatures. A pronounced decrease in the mean daily temperatures could be seen at New Delhi which is characterized by cool winter season.

iii) Potential evapotranspiration and its relationship to rainfall: In the low latitudes near about the equator one of the dominant factors in water is the large amount of energy available for evaporation. Since solar radiation happens to be the most important component effecting evaporation and since its variation from year to year is more or less constant, potential evapotranspiration is more or less constant from year to year. The degree of variation in PE on a seasonal basis reflects variations in altitude of the sun, cloud cover, wind speed and humidity.

On an annual basis, Budyko (1956) showed that only a small part of the tropics has rainfall in excess of evaporative demand. This annual picture is misleading; seasonal variations in both evaporative demand and even more so in rainfall will in most cases produce periods when the latter is in excess of the former and vice versa. Davies and Robinson (1969) showed marked spatial contrasts in the difference between precipitation and potential evapotranspiration in Africa.

When rainfall exceeds potential evapotranspiration, soil-moisture reserves are recharged. On the other hand when rainfall is less than PE, soil moisture reserves are utilized. Once soil moisture drops below field capacity, however, water may not be freely available. The work of Denmead and Shaw (1962) showed that the ability of the soil to supply water is one of the most important factors to be considered in relation to the crop water supply. As shown in Table 4 the volumetric moisture content plays an important role in determining the ratio of the actual supply of water to the potential water supply (termed AE/PE). If the volumetric soil moisture is about the field capacity level then irrespective of the potential evapotranspiration or the demand, the plants will be able to take water at a potential rate. But on the other hand if the volumetric soil moisture content drops down to 32% the plants will be able to take up water at a potential rate

Table 3. Monthly variation in the mean daily maximum and mean daily minimum temperatures at the four locations.

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bamako	32.8	36.1	38.9	39.4	38.9	34.4	31.7	30.6	31.7	33.9	34.4	33.3
	16.1	18.9	21.7	24.4	24.4	22.8	21.7	21.7	21.7	21.7	18.3	16.7
Niamey	33.9	36.7	40.6	42.2	41.1	38.3	34.4	31.7	33.9	38.3	38.3	34.4
	14.4	17.2	21.7	25.0	26.7	25.0	23.3	22.8	22.8	23.3	18.3	15.0
Dakar	26.1	26.7	26.7	27.2	28.9	31.1	31.1	30.6	31.7	31.7	30.0	30.6
	17.8	17.2	17.8	18.3	20.0	22.8	24.4	24.4	24.4	24.4	22.8	19.4
Hyderabad	28.6	31.2	34.8	36.9	38.7	34.1	29.8	29.5	29.7	30.3	28.7	27.8
	14.6	16.7	20.0	23.7	26.2	24.1	22.3	22.1	21.6	19.8	16.0	13.4

Table 4. Changes in AE/PE with soil moisture and evaporative demand. (After Denmead and Shaw, 1962)

Volumetric Soil Moisture (%)	AE/PE		
	Daily Potential Evapotranspiration (mm)		
	2.0	4.1	6.4
36 - Field capacity	1.00	1.00	1.00
32	1.00	0.98	0.40
28	0.98	0.90	0.15
24	0.75	0.38	0.03
22 - Permanent Wilting	0.35	0.12	0.00

only at a low demand whereas if the demand is higher the soil will not be able to supply water to the plants. If the volumetric soil moisture content comes down to 24%, the plants will be able to take up water only at a very low demand. Hence it needs to be mentioned that the crop yields are proportional to the moisture availability. There is an optimum range of moisture availability at which the crops will be able to yield the maximum. Beyond this optimum range one encounters the upper limit and the lower limit.

As shown in Figure 2, at stations such as Bamako, the short wet season provides 3-4 months when rainfall exceeds PE, allowing some soil moisture recharge followed by utilization of this in succeeding months when, however, the deficit is still marked. With uneven seasonal distribution of precipitation and with great inter-annual variability, small negative deviations in precipitation are all that are required to initiate drought. In semi-arid India moderate or worse droughts are likely to occur one year in every four (Fig. 3).

In most years the rainy season in the semi-arid tropics is long enough for crops to grow. Indeed there is usually excess water in the rainy season, some of which can be stored in the soil, but most of which runs off cuasing soil erosion. Management of land, crops and livestock are intimately associated with the inflow and outflow of water. In determining the agricultural potentials of any semi-arid area, quantification of the timing, amount and duration of rainfall, the intake, storage and release of soil moisture and the evapotranspiration is essential. For example, Virmani et al. (1978) using a water balance model incorporating these factors have shown that the length of the growing season at ICRISAT Center on shallow sandy red soils (Alfisols) fluctuates from 12 to 21 weeks and on deep clayey black soils (Vertisols) from 20 to 31 weeks (Table 5). The soil type clearly plays an important part in defining length of growing season in a given climatic situation.

iv) High intensity-high volume storms: Another characteristic of the rainfall environment of the dry tropics is that substantial portion of the rainfall is received in a few high intensity high volume storms. Data for two typical years 1979-80 for ICRISAT Center are given in Table 6. The results show that intensity of rainfall ranges between 20 to 60 mm in most instances, but may be as high as 120 or 160 mm/hr in some instances. The frequency of occurrence of intensive rainfall spells of high intensity observed at ICRISAT Center between 1974 and 1979 is given in Table 7.

3. APPROACHES AND FINDINGS

Despite the complexity of the situation as presented above, certain broad generalizations can be made. The character of rainfall in a particular month (e.g. intensity, duration etc.) and the elements of the atmosphere -- soil-plant system determining the effectiveness of rainfall in relation to evaporative demand make it impossible to define a 'wet' month. Use of monthly averages to describe seasonal regimes is often times suspect not only because rainfall conditions

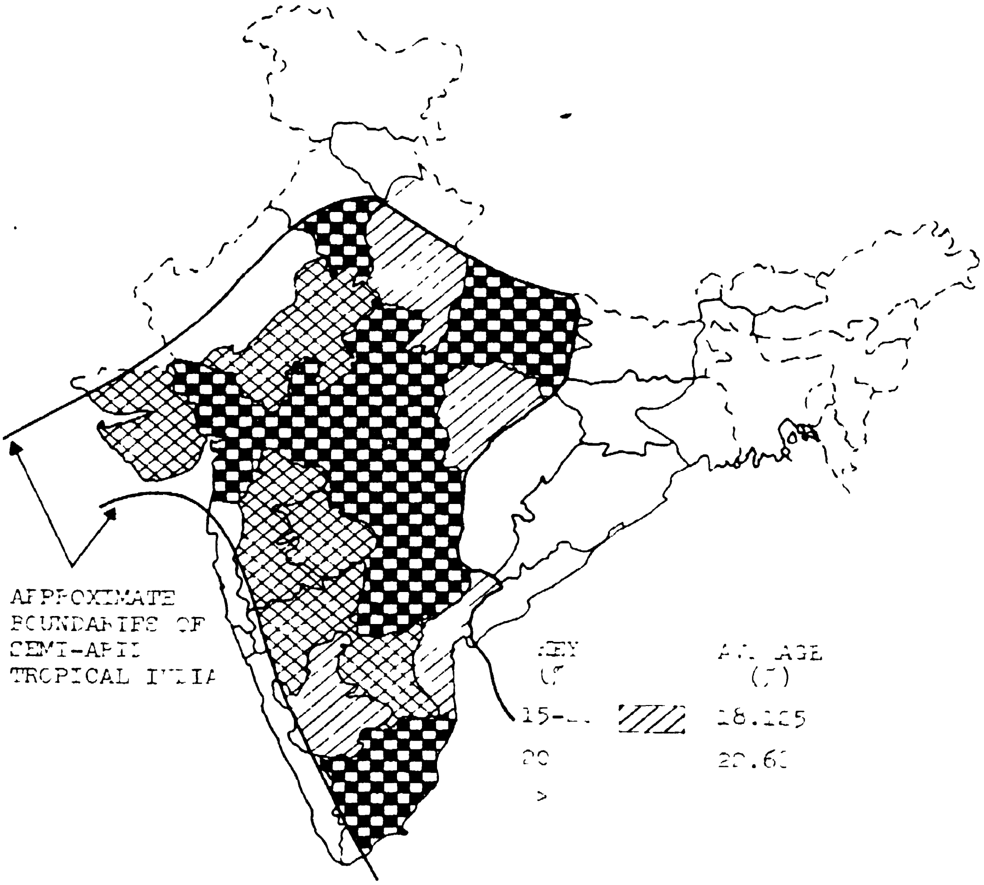

Figure 3. Percentage occurrences of droughts of class moderate and worse in the rainy season in the Indian semi-arid tropics.

Table 5. Length of the growing season (in weeks)[a] for three soil conditions.[b]

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

[a] From seed-germinating rains (25 June) to end of season [time when profile moisture reduces AE/PE (Ratio of actual evapotranspiration to potential evapotranspiration) to 0.5].

[b] Low: shallow Alfisol; medium: shallow to medium-deep Vertisols; high: deep Vertisol.

Table 6. Frequency of occurrence of intensive rain spells at ICRISAT Center.

Year	Intensity (mm/ha) > 10	 > 20	 > 40	 > 60	Annual rainfall[1] (mm)
1974	14	6	0	0	833
1975	31	18	9	5	1029
1976	31	18	7	3	679
1977	14	14	4	0	35
1978	34	22	11	5	77
1979	21	16	10	3	31
Average	24	16	7	3	797
%	100	67	29	12	

[1] June to October.

Table 7. Duration and amount of intensive rain spells two rainy seasons.

Date	Duration (min)	Rainfall[1] (mm)	Inten (mm/hr
24-06-79	15	6.0	24
08-07-79	15	8.0	32
23-07-79	15	12.5	50
28-07-79	15	30.0	120
02-08-79	15	13.5	54
28-08-79	15	10.0	40
10-09-79	15	5.0	20
11-09-79	17	12.0	42
14-09-79	15	15.5	62
22-09-79	10	8.0	48
23-09-79	15	20.0	80
24-09-79	15	5.0	20
25-09-79	15	6.5	26
27-09-79	15	30.0	120
01-10-79	15	8.0	32
05-11-79	15	40.0	160
		1980	
02-06-80	15	10.0	40
12-06-80	15	14.0	56
15-06-80	15	10.0	40
16-06-80	15	6.5	26
01-07-80	15	13.0	52
22-07-80	15	10.0	40
23-07-80	15	12.0	48
30-07-80	15	11.5	46
06-08-80	15	11.0	44
19-08-80	15	14.5	58
20-08-80	15	14.0	56
03-09-80	15	9.0	36
06-09-80	15	15.5	62
18-09-80	15	7.0	28
22-09-80	15	6.5	26
24-09-80	15	5.5	22

[1] High intensity spells recording 5 mm/15 minutes are considered.

during short time periods are critical for agriculture but also because the onset and the end of season -- either on average or for individual years -- do not coincide with calander months. Also in low rainfall areas, extremes have considerable import upon averages and hence the latter are of little value.

At certain times in the growth season of a crop, presence or absence of water is critical and hence indications of variability over short time periods are of great importance. Many agricultural operations revolve around the probability of receiving given amounts of rainfall. Large scale operational planning often requires decision making with respect to resources, man power needs, available work days and several other factors. A comprehensive idea regarding the probabilityof rainfall receipts is essential in view of the economic implications of certain weather sensitive operations.

In determining the rainfall probabilities, fitting a mathematical function to rainfall data and computing the probabilities from this function is a common approach. In the probability analysis of daily rainfall data, two approaches -- constant precipitation analysis, and constant probability analysis -- have been adopted.

a) Markov Chain Constant Precipitation Analysis of Weekly Rainfall

Weekly precipitation totals can be analyzed using first order Markov chain for the probability of receiving a certain amount of precipitation -- for example 5, 10, and 20 mm. The program used for the computation of initial and conditional probabilities is listed by Sivakumar et al. (1979).

Results are reported for the initial probabilities of a wet week, P(W); conditional probabilities of a wet week following a wet week, P(W/W); and of a wet week following a dry week, P(W/D). A discussion of the formulae employed in the calculation of these probabilities has been presented by Virmani et al. (1978).

Constant precipitation analysis has been carried out for those stations with rainfall records exceeding 15 years to cover 100 locations in India and about 300 locations in West Africa. Results of the constant precipitation analysis are presented for 77 locations of Niger in the ICRISAT Information Bulletin 5 'Rainfall Climatology of West Africa: Niger' and for 77 locations of India in an enlarged second edition of the ICRISAT Research Bulletin No. 1, 'Rainfall Probability Estimates for Selected Locations of Semi-Arid India.'

i) Application of probability analysis for defining moisture environment of a location: Discussion of some of the methodologies and approaches that have been adopted at ICRISAT for investigation of climatic water availability is given below, taking the Hyderabad region as an example (Table 8). 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 (0.85-1.37). August and September show a positive moisture balance. In the postrainy season, rainfall is not adequate to meet potential demand.

Table 8. Climatic water availability at Hyderabad, India.

Month	Mean rainfall-R (mm)	Mean PE (mm)	R/PE	Dependable precipitation (mm)[a]	MAI[b]
Jan	2	110			
Feb	10	129		0	
Mar	13	181		0	
Apr	23	198		6	0.03
May	30	220		7	0.03
Jun	107	196	0.55	59	0.32
Jul	165	140	0.85	121	0.75
Aug	147	135	1.09	86	0.55
Sep	163	119	1.37	91	0.65
Oct	71	124	0.57	30	0.21
Nov	25	104	0.24	0	
Dec	5	99		0	

[a] At 75% probability, also referred to as PD.

[b] Moisture Availability Index = PD/PE.

The mean monthly rainfall data do not yield information on the dependability of precipitation to meet potential demand. Hargreaves (1975) has defined dependable precipitation (PD) as the amount of rainfall which could be received at 75% probability. It is evident that the 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 4. 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. Using these probabilities, Virmani et al. (1978) showed that differences in the performance of a given cropping system at Hyderabad and Sholapur during the rainy season could be interpreted in terms of the initial and conditional probabilities of rainfall.

One application of such analysis 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 (Fig. 5) 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. Dry seeding is an important component of the improved technology for deep Vertisols (Srivastava et al. 1982). The dry seeding period for rainy season crops will be a couple of weeks ahead of the onset of seasonal rainfall which is abrupt at Hyderabad and the probabilities of continuance of rain are high. Therefore this location offers excellent scope for dry seeding. At locations such as Sholapur, 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

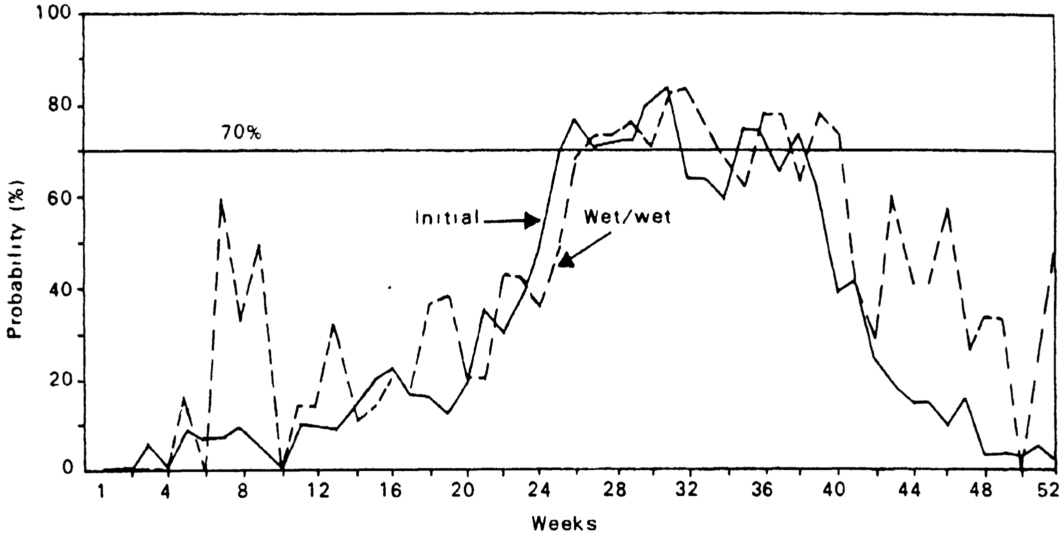

Figure 4. *Probabilities of rainfall (RIPE≥0.33) at Hyderabad (1901–1970 data)*

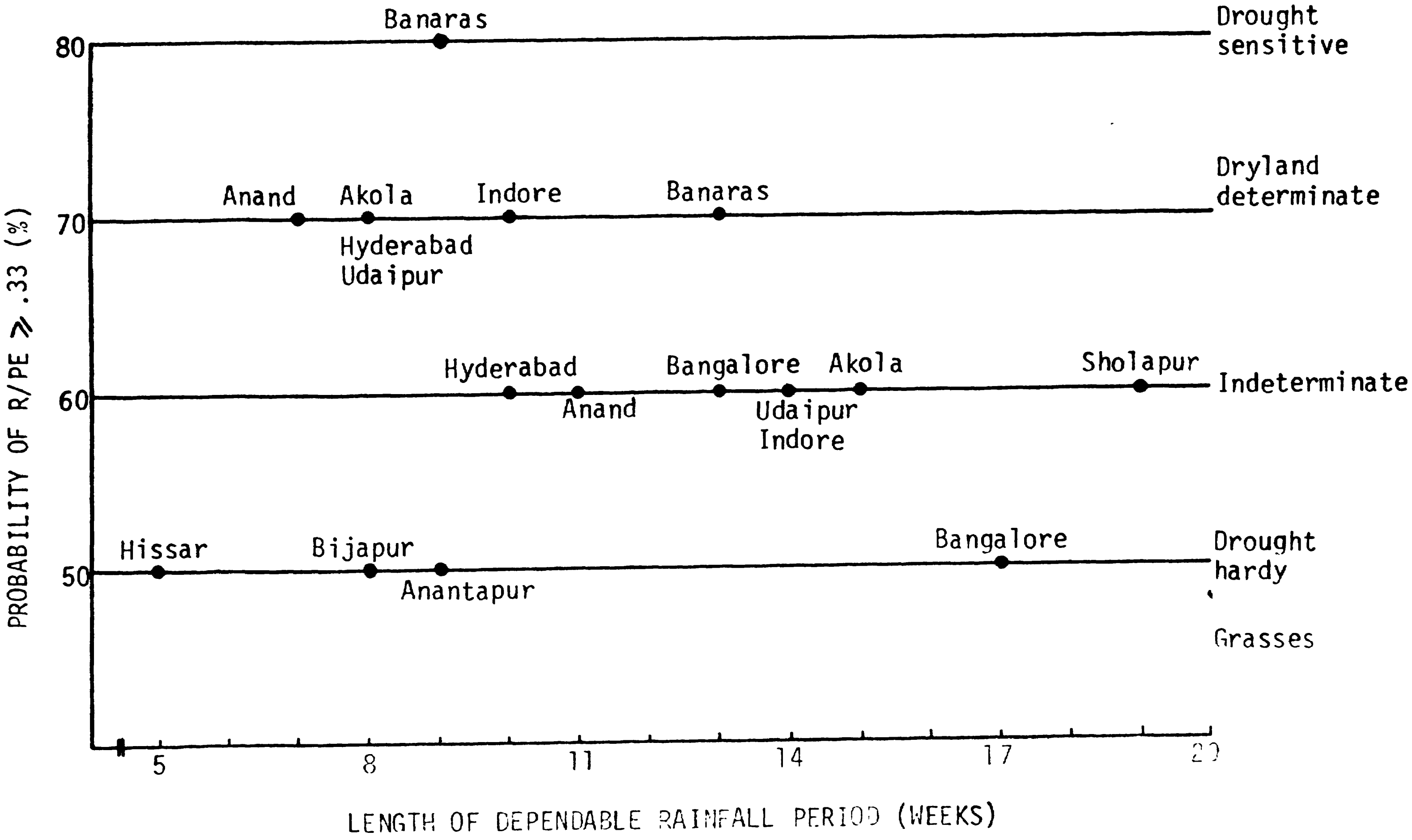

Figure 5. Relationship between dependable rainfall and suitable crops at selected locations.

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 6. 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.

The area of dependable rainfall can also be identified using this methodology. An example is given in Figure 7. The areas of deep Vertisols in India where farming systems technology developed at ICRISAT would probably be successful are delineated (Virmani et al. 1981).

b) Constant Probability Analysis for Monthly Rainfall

In most cases one of the first things that one wants to know for a location is its agricultural potentialities for dryland agriculture. Hargreaves method could be adopted as an index for measuring water deficiencies and excess. Hargreaves suggested the following classification for dryland agriculture:

MAI = 0.00 to 0.33 moisture very deficient
= 0.34 to 0.67 moisture moderately deficient
= 0.68 to 1.00 moisture somewhat deficient
1.01 to 1.33 moisture adequate
= > 1.34 excessive

It is to be remembered that moisture adequacy at a given location depends also on the soil conditions. In the absence of adequate information on the soil type, its water storage and release characteristics; MAI can provide an approximation of water availability.

The constant probability analysis can be carried out by using Incomplete Gamma distribution functions. A computer program to carryout such analysis is available at the ICRISAT computing unit.

A handbook on the Rainfall Climatology of West Africa (Virmani et al. 1980) has been prepared. It gives information on rainfall, PE and dependable precipitation for over 280 locations located between 7° and 15° north latitude and 17° west and 24° east latitude, covering a total area of 4.2 million km^2. An examplified data set for a few

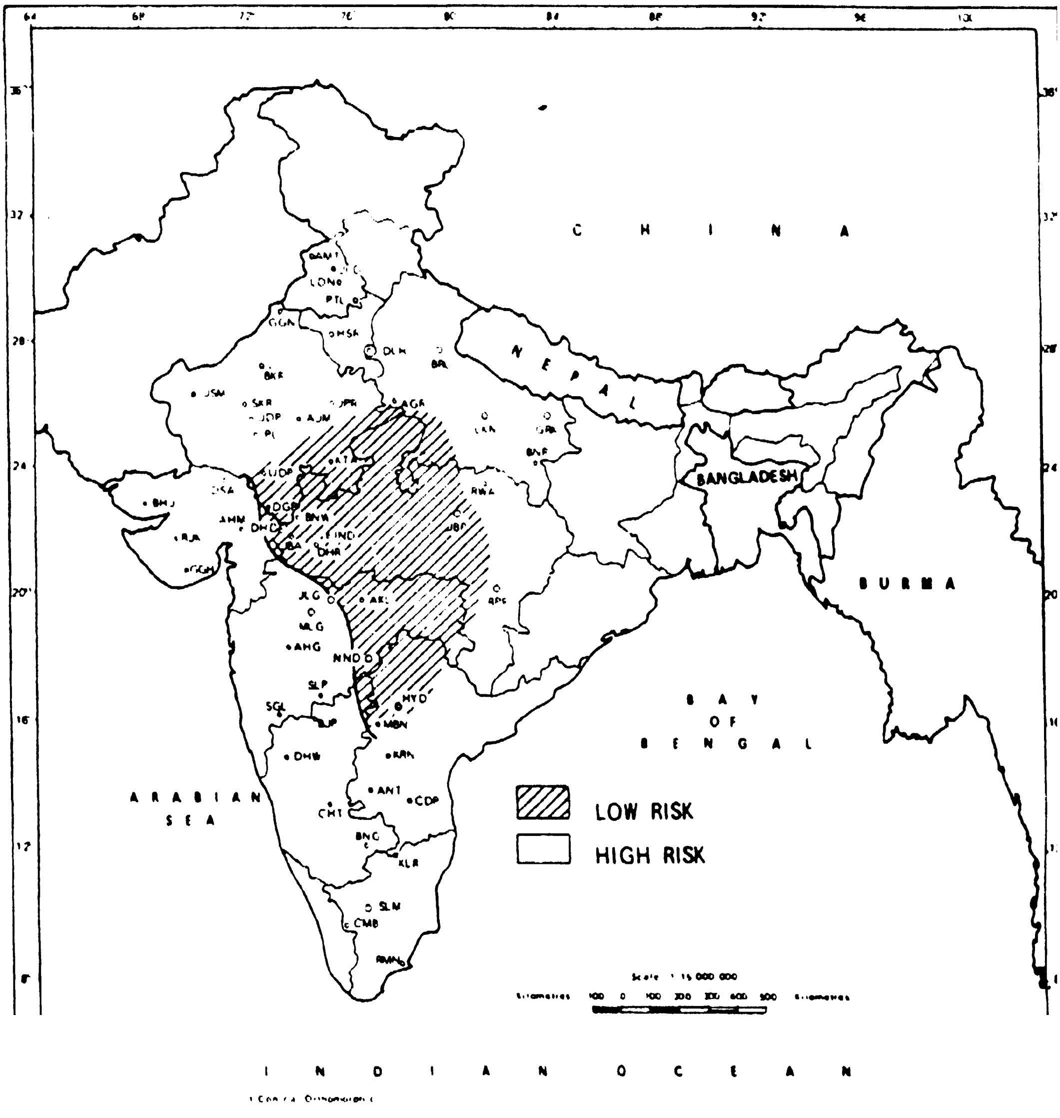

Figure 6. Possibilities of dry seeding on Vertisols.

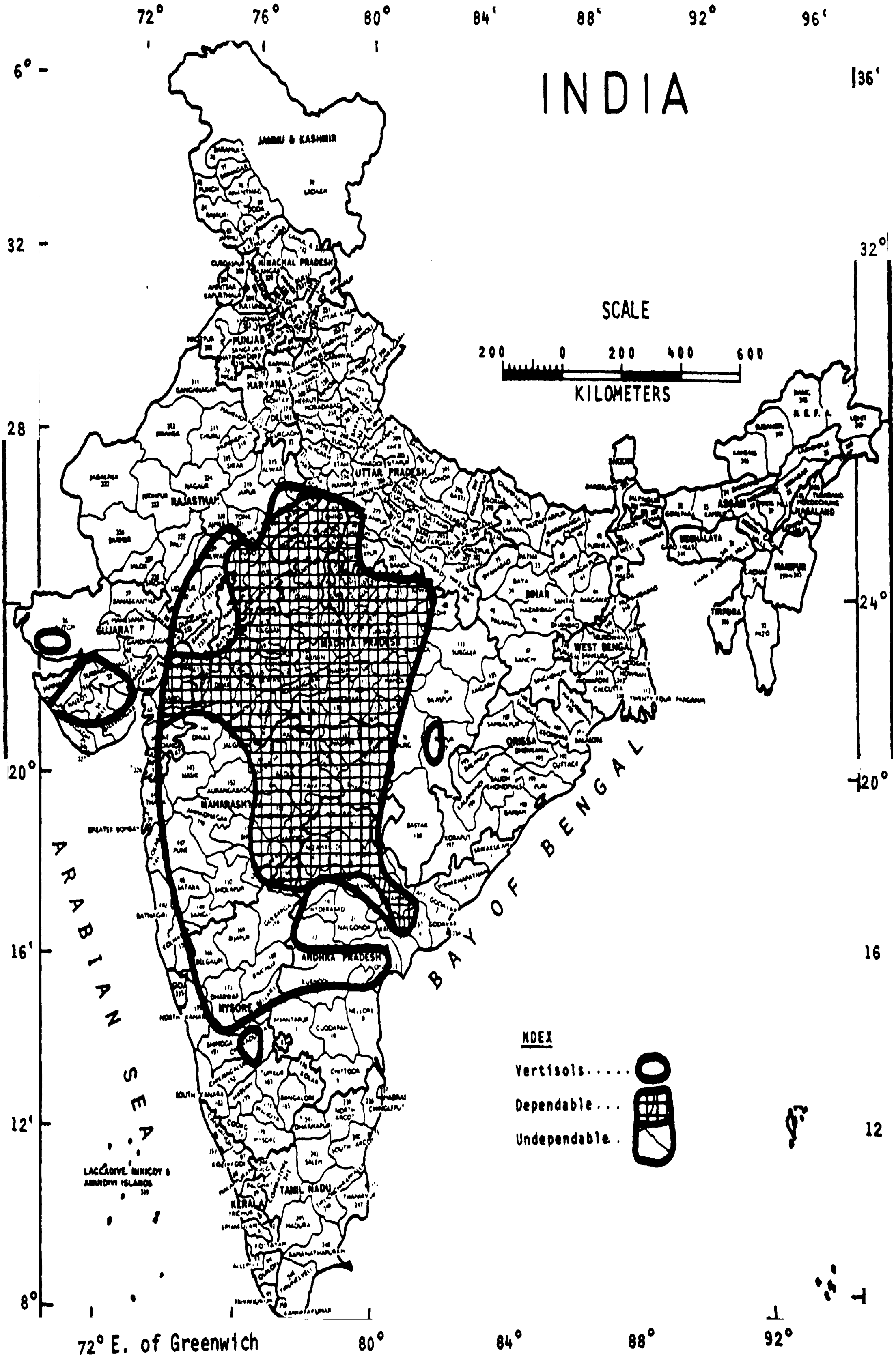

Figure 7. The Vertisol areas of India where rainfall is dependable and undependable.

locations in Mali is shown in Table 9. The data show that at Bamako the MAI exceeds 0.33 for 4 months from June to September; the moisture availability is excessive in the months of July, August and September. On the other hand the data for Douentza and Gao reveal that MAI exceeds 0.33 value only for two months of July and August and at Gao only in the month of August.

Such an analysis could clearly demonstrate the agricultural potentials of the area, the length of the core growing season and climatic moisture balance for the rainy months. For example a 120-day crop could be easily grown at Bamako, a 60-day crop at Douentza; the Gao area is not suitable for crop land agriculture. The rainy season is too short.

c) 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 is 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 McAlpine 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, there is a fair degree of storage for a fairly longer time during the growing season. Thus, under identical rainfall conditions, the effects of short-term intra-seasonal droughts on crop-moisture status will differ in the three 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.

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 with 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 conditions 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 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.

Table 9. Mean monthly rainfall (P), dependable precipitation (PD), and potential evapotranspiration (PE) at three locations in West Africa.

Location		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annua
Bamako	P	0	0	4	17	64	142	241	325	213	63	9	0	1079
	DP	0	0	1	5	33	106	195	256	157	27	0	0	
	PE	143	160	204	198	185	152	125	113	119	135	128	134	1796
	MAI				0.02	0.18	0.70	1.56	2.26	1.32	0.20			
Douentza	P	0	0	2	4	17	67	132	167	87	19	0	0	497
	DP	0	0	0	1	4	39	97	126	50	4	0	0	
	PE	145	164	210	223	214	198	160	143	146	154	140	130	2027
	MAI					0.02	0.20	0.61	0.88	0.34	0.03			
Gao	P	0	0	0	1	6	25	72	111	36	5	0	0	258
	DP	0	0	0	0	1	10	46	76	17	2	0	0	
	PE	141	165	213	221	246	227	200	171	182	181	147	141	2235
	MAI						0.04	0.23	0.44	0.09	0.01			

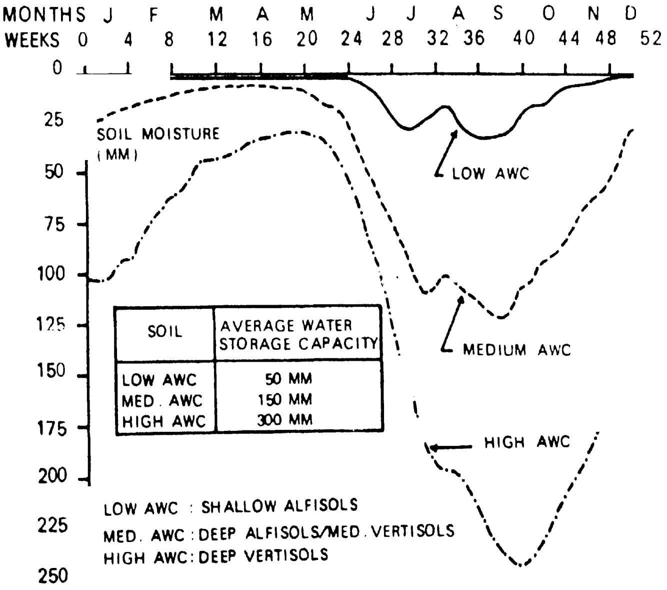

Figure 8. Weekly soil-moisture storage in three soils (Hyderabad 1901-70 data).

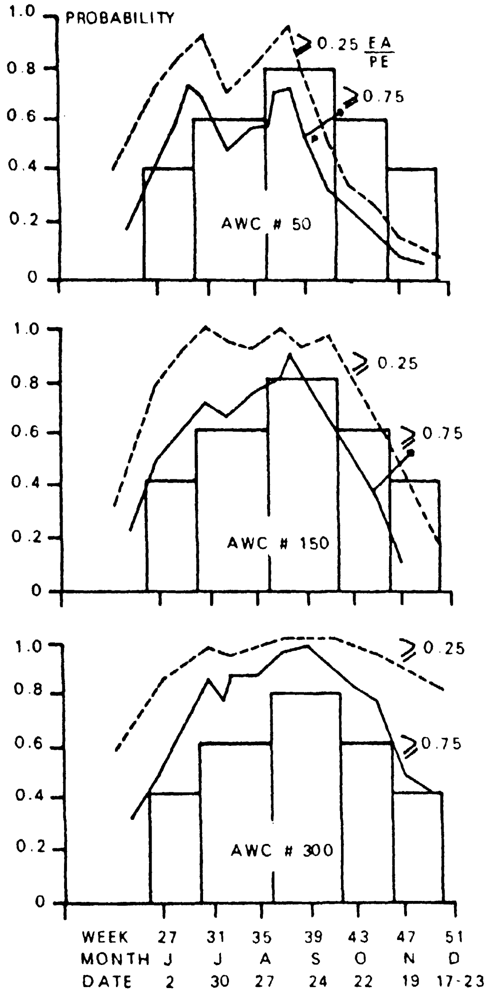

Figure 9a Fitting of a long-duration crop in three soils.

(BARS = CROP WATER REQUIREMENT AND CURVES = WATER AVAILABILITY AT TWO PROBABILITY LEVELS)

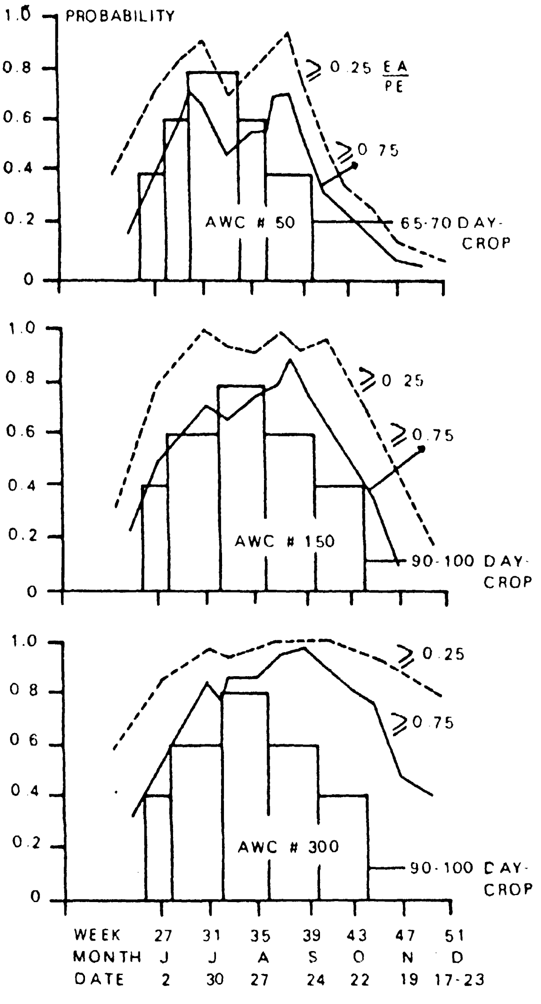

Figure 9b Fitting of short – (65 to 70 days) and medium – (90 to 100 days) duration crops in three soils.

(BARS = CROP WATER REQUIREMENT AND CURVES = WATER AVAILABILITY AT TWO PROBABILITY LEVELS)

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 at different durations (Table 10). The importance of such field work-day probabilities in relation to harvest of sorghum in two soil types is 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 the 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.

LOOKING AHEAD

As referred by the Technical Advisory Committee (TAC) while reviewing the Farming Systems Research (FSR) at International Centers (TAC 1978), base data analysis is inimical to the success of any program using the FSR approach. Climate evaluation which includes presentation of general climatic characteristics of different regions and assessment of crop potential is an important first step in planning for the resource-based technologies for improved crop production in the SAT. Our work in this area would place emphasis on the following aspects:

- Providing meaningful climate classification using different methodologies for outlining crop potentials for different regions and to assist in transfer of technology,
- Continuing the studies on rainfall climatology to provide first approximation answers to water availability and the associated spatial and temporal variability, and
- Computing the water balance of different SAT areas so as to evaluate the traditional systems of cropping using the simulated water balance components and to seek alternative technologies for improved crop water use efficiencies.

Table 10. Field-work day probabilities at harvest of sorghum and millet crops at Hyderabad.

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

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PROFILE WATER DYNAMICS IN ALFISOLS AND VERTISOLS IN RELATION TO ROOT DISTRIBUTION[1]

Piara Singh, Gamini Gunasekara, and Sardar Singh[2]

SUMMARY

Water balance and water dynamics of a soil profile are affected by several factors, viz., physical characteristics of a soil profile, topography, crop cover, and the above ground environment. Since water is one of the most limiting factors in agricultural production in the semi-arid tropical (SAT) regions, it is very important to quantify the productive and unproductive losses of water for the evaluation of a water management system and for meaningful interpretation of experimental results. This report presents some work done at ICRISAT Center during the period from 1973 to 1979 on the quantification of water balance and soil profile water dynamics of Alfisols and Vertisols in selected crops or cropping systems. It is emphasized that for more agronomically meaningful description of a soil profile as reservoir for water, we must quantify the availability of water in relation to root distribution and crop growth stage.

1. INTRODUCTION

Water is one of the most limiting factors in crop production in the semi-arid tropical (SAT) regions of the world. Thus, yields of crops depend on the water availability at various plant growth stages. Rainfall in SAT is very erratic and soil profile acts as a means to store and supply water to a crop to meet the continuous evapotranspirational demand. Various soil, crop, and environmental factors that govern the water availability to a crop must be understood for meaningful interpretation of experimental results of a study concerning the management of water. For instance, properties of soil profile affect the intake, runoff, retention, drainage and loss of water as evaporation and transpiration. Plant characteristics such as rooting determine the ability of a crop to tap and transmit water to the above ground parts. Amount and distribution of rainfall during the cropping season influence water availability at various plant growth stages. Therefore, the interactions among climatic, edaphic, and plant factors must be studied to improve resource management and to increase crop production in any area. Thus studies were done at ICRISAT Center on water balance and profile water dynamics throughout the cropping season. The objective of this report is to present results on:

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[1] Paper for presentation at the IRAT-ICRISAT Workshop on Water Management and Crop Production, Montpellier, France, 3-6 May 1982.

[2] Soil Scientist, Principal Soil and Water Scientist and Soil Scientist, respectively, ICRISAT.

- The quantification of soil profile water dynamics and water balance of Alfisols and Vertisols.
- To examine the relationship of rooting of crops to profile water depletion.

2. APPROACH AND METHODOLOGY

These studies were done at ICRISAT Center in Alfisols and Vertisols which form the major soil groups of SAT. Detailed information on physical and chemical properties of a typical Alfisol and Vertisol soil profile are given in Appendix 1 and 2 respectively. Some physical properties are described below.

a) Alfisols

Alfisols profiles are heterogenous with marked variation 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 density commonly ranges from 1.5 to 1.95 g/cm^3 and the percentage of particles >2.0 mm ranges from 0 to 70%. Therefore, it is necessary to measure both these quantities at several points in each of these areas being studied to arrive at the site-specific profile water storage capacity for use in quantitative water balance and crop water use studies.

b) Vertisols

The Vertisol profiles are physically quite homogeneous and isotropic. The bulk density of 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 to 1.45 g/cm^3 with an average of 1.4 g/cm^3.

c) Plant Extractable Water

Plant extractable water on deep and medium-deep Alfisols and Vertisols is presented in Figure 1. Upper limit of profile water storage is defined as the maximum amount of water retained in the rooting zone after its complete saturation and drainage of free-water. Lower limit of plant available water is defined as the minimum amount of water content left in the profile as measured in the field under a well-managed deep-rooted long-season crop grown in the postrainy season. 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. For the calculations of plant extractable water the rooting depth for deep Vertisols, medium-deep Vertisols, and deep Alfisols is 187 cm and for medium-deep Alfisols it is 157 cm. Upper limit of plant available water for deep Vertisol, medium-deep Vertisol, deep Alfisol and medium-deep Alfisol is 810 mm, 700 mm, 430 mm, and 315 mm, respectively (Fig. 1). Corresponding lower limit values for the soils in the same sequence are 580 mm, 540 mm, 290 mm, and 220 mm, respectively. Thus,

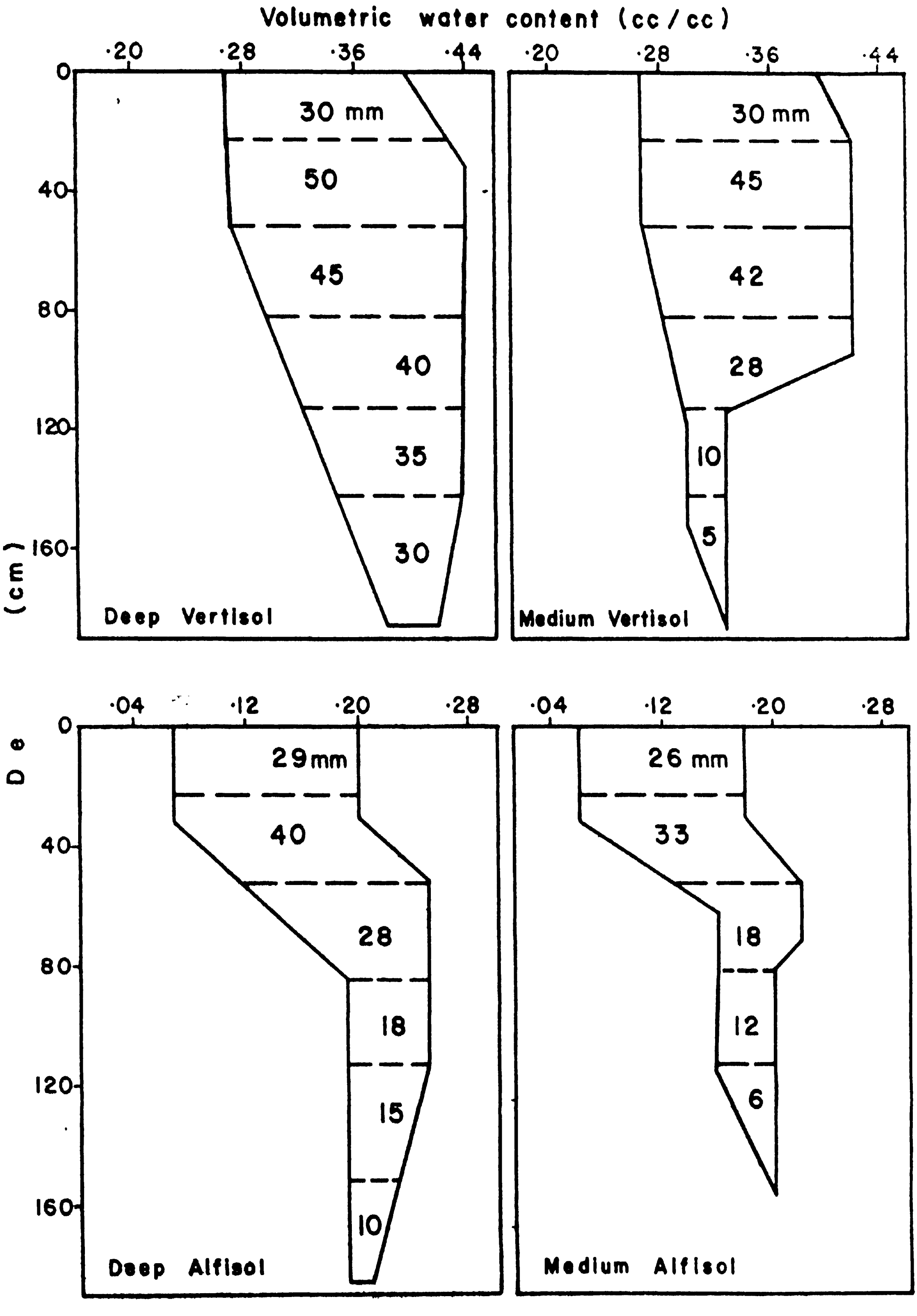


Figure 1. Available water profiles for four soils (Environmental Physics Report, 1977-78).

plant extractable water for the deep and medium-deep Vertisol is 230 mm and 160 mm, respectively, Similar values for deep and medium-deep Alfisol are 140 mm and 95 mm, respectively (Fig. 1).

d) Root Studies

These studies were done in the 1974-75 cropping season in both Vertisols and Alfisols. A 7.6 cm diameter soil sampling tube mounted on a hydraulically operated coring machine was used for taking root samples. The plants were cut at the soil surface and soil cores, each of 15 cm length, were taken to 180 cm soil depth or to the depth of a hard pan. These soil samples were enclosed in polyethylene bags and transported to the laboratory where they were soaked in water for a overnight and then washed to separate out roots. Root length in each sample was measured and expressed as cm/cm^3 of soil.

e) Water Balance and Profile Water Dynamics

These studies were done during the 1977-78 and 1978-79 cropping seasons on Vertisols and during the 1977-78 season on Alfisols. On Vertisols the plot size varied from 0.12 ha to 3.0 ha. On Alfisols the plot size in the rainy season was 9 x 10 m and the plots were diked to prevent runoff in the rainy season. In the postrainy season runoff did not occur on Alfisols. In Vertisols, runoff was measured by water stage recorders and V-notch weirs on the plots and by a Parshall flume on the watershed. Following components of water balance equation were quantified:

$$P + I = \Delta M + R + D + E + T_m$$

Where, P = precipitation, I = irrigation, ΔM = change in profile water content, R = runoff, D = drainage, E = soil evaporation, T_m = mass balance transpiration.

Daily soil evaporation was measured from the following relationship as given by Russell (1978).

$$E = \beta (Eo/t)$$

Where, Eo = open pan evaporation, t = number of days following a rain of sufficient size to recharge the surface 10 cm of soil, β = fraction of radiation reaching the soil surface that could be measured or estimated from leaf area index.

Changes in water content $(\overline{\Delta M})$ below 22 cm profile depth were measured by the neutron moderation technique and for the surface 22 cm by gravimetric sampling. Evapotranspiration (ET) for various growth periods was computed by adding profile water change (ΔM) and effective rainfall (precipitation minus runoff). Mass balance transpiration (T_m) was calculated by substracting soil evaporation from evapotranspiration. Another estimate of transpiration based upon energy balance considerations (T_e) was computed as $T_e = E_0 (1-\beta)$. This assumes no advection and no water stress. T_e was compared with T_m for various crop growth periods to indicate crop water stress. On the day when effective rainfall plus antecedent profile water content exceeded the storage capacity of the soil, the excess water was considered as deep drainage. Time and depth changes in hydraulic head were measured with tensiometers to indicate the direction and magnitude of the vertical hydraulic gradients within the profile especially across its lower boundary to verify drainage. This also indicated the onset of soil water stress in the root zone.

3. SUMMARY OF RESULTS

a) Rooting of Crops in Alfisols and Vertisols

Root studies done at 50% flowering stage of crops show that most of the crops studied had their roots extended down to 180 cm profile depth, except in chickpea, setaria and chillies where the roots penetrated to 150 cm profile depth (Table 1). Crops also differed in their root density in a given layer. Deep penetration of roots in Vertisols could be attributed to the uniformity of soil profile and more availability of water in subsoil. In an Alfisol, in most of the crops roots extended to 150 cm profile depth (Table 1). The less deep root system in Alfisols could be attributed to the frequent water stress experienced by the plants because of the low water holding capacity of the Alfisols and also due to the presence of a stoney layer of high bulk density in the subsoil which is locally called 'murrum.'

In addition to the total root mass produced and rooting depth, there are differences in the distribution of roots in Alfisols and Vertisols (Table 2). In Alfisols most of the roots are confined to the upper 1/3rd of the soil profile and it has relatively less proportion of roots in the middle 1/3rd and lower 1/3rd of profile as compared to those in Vertisols.

b) Profile Water Use by Crops

Since water is one of the most limiting factors in the SAT environment, water use by crops is of considerable interest to the farming systems research program. During the 1977-78 season the following experiments have been carried out:

- Water use by rainy and postrainy season crops grown on a deep Vertisol.
- Profile water use by sorghum from an Alfisol.
- Profile water use by pearl millet from an Alfisol.
- Profile water dynamics in uncropped Vertisols and Alfisols.

These studies serve as an example of the pattern of crop water use and profile water dynamics on Vertisols and Alfisols.

Table 1. Root distribution of various crops in Vertisols and Alfisols Values given are an average of three samplings. Data taken from Annual Report of Farming Systems Research Program, 1974-75'.

Soil depth (cm)	Vertisol								Alfisol					
	Sorghum	Saf-flower	Sun-flower	Cotton	Chick-pea	Pigeon-pea	Setaria	Chillies	Sorghum	Pearl-millet	Sun-flower	Pigeon-pea	Castor	Tomat
	Root density (cm of root/cm^3 of soil)													
0-30	0.19	0.16	0.36	0.21	0.16	0.22	0.28	0.13	0.15	0.48	0.24	0.18	0.17	0.17
30-60	0.07	0.07	0.05	0.15	0.15	0.07	0.17	0.03	0.06	0.11	0.08	0.14	0.10	0.03
60-90	0.06	0.11	0.07	0.13	0.21	0.08	0.11	0.02	0.08	0.09	0.04	0.09	0.06	0.01
90-120	0.04	0.08	0.03	0.03	0.04	0.04	0.02	0.01	0.07	0.04	0.01	0.06	0.03	0.01
120-150	0.01	0.05	0.01	0.01	0.00	0.02	0.003	0.001	0.06	0.04	0.004	0.02	0.01	0.00
150-180	0.01	0.02	0.01	0.003	0.00	0.01	0.00	0.00	0.01	0.004	0.00	0.00	0.00	0.00

Table 2. Percent roots of various crops in three soil zones in Vertisols (V) and Alfisols (A). Data taken from Farming Systems Research Program Annual Reports, 1973-74 and 1974-75 .

Soil zone	Sorghum		P. Millet		Pigeonpea		Chickpea		Safflower		Sunflower		Maize	
	V	A	V	A	V	A	V	A	V	A	V	A	V	A
	Percent of total root density													
Upper 1/3 (0-60 cm)	63.9	66.8	61.8	78.5	66.4	64.5	58.4	76.6	50.3	59.8		84.7	87.2	92.1
Middle 1/3 (60-90 cm)	27.2	26.0	30.9	17.0	27.2	31.0	36.9	21.3	36.1	33.1	22.2	14.4	8.6	7.9
Lower 1/3 (90-120 cm)	7.8	10.8	7.2	4.0	6.4	4.5	9.1	2.0	13.5	4.6	7.2	0.9	3.5	0.0

i) Water use by rainy and postrainy season crops grown on a deep Vertisol: Time and depth patterns of profile recharge and depletion were measured under several crops during both the rainy and postrainy seasons. Data were obtained on the deep Vertisol for maize, sorghum, pigeonpea, and maize/pigeonpea intercrop during the rainy season and for irrigated and rainfed sorghum and chickpea and for rainfed pigeonpea during the postrainy season.

During the rainy season the time and depth patterns of profile water content under the various crops were similar to those under the maize/pigeonpea intercrop and maize (Figs. 2A and B). The curves clearly show the seasonal downward progression of the recharging process and the cyclical recharging and depletion of the upper part of the Vertisol profile. At the start of the rainy season the profile was depleted below the 15-bar value to a depth of 30 to 45 cm. Below this the 187 cm profile contained about 80 mm of water above the 'de facto' lower limit of water availability shown as a broken line in Figure 2.

The progressive depletions of profile moisture during the postrainy season by unirrigated pigeonpea, chickpea and sorghum are shown in Figure 2 C-E. The depletion that occurred during the rain-free period in mid-September and the partial recharging of the upper part of the profile by the early October rains are apparent from the curves. Differences in the time course of depletion at various depths by the pigeonpea, sorghum and chickpea crops also are clear from the curves.

The changes in available water in six layers of the deep Vertisol profile during the postrainy season under rainfed and irrigated sorghum are summarized in Table 3. For the rainfed crop the small rains during the growing season only partially recharged the 0-22 cm layer. The deeper layers all lost water progressively. In the irrigated plots the effects of the rains were supplemented by irrigations on 18 November and 19 December which recharged the entire profile. As a result of those cyclical refillings and depletions the total water extracted during the season from the various soil layers exceeded the capacity of those layers, mostly of the irrigated plots. The 'capacity use factors' (CUF) i.e. the seasonal withdrawal divided by the layer capacity for each of the six layers 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.

The amount of water extracted by roots of rainfed pigeonpea from the deep Vertisol during five periods of the postrainy season are summarized in Table 4. The rains during that season only partially recharged the upper two profile layers. The data in Table 4 were calculated from the profile depletion curves and from daily water balances for the periods following rains. For the season the crop obtained 57 percent 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 pigeonpea roots were effective in removing water throughout the entire 187 cm Vertisol profile.

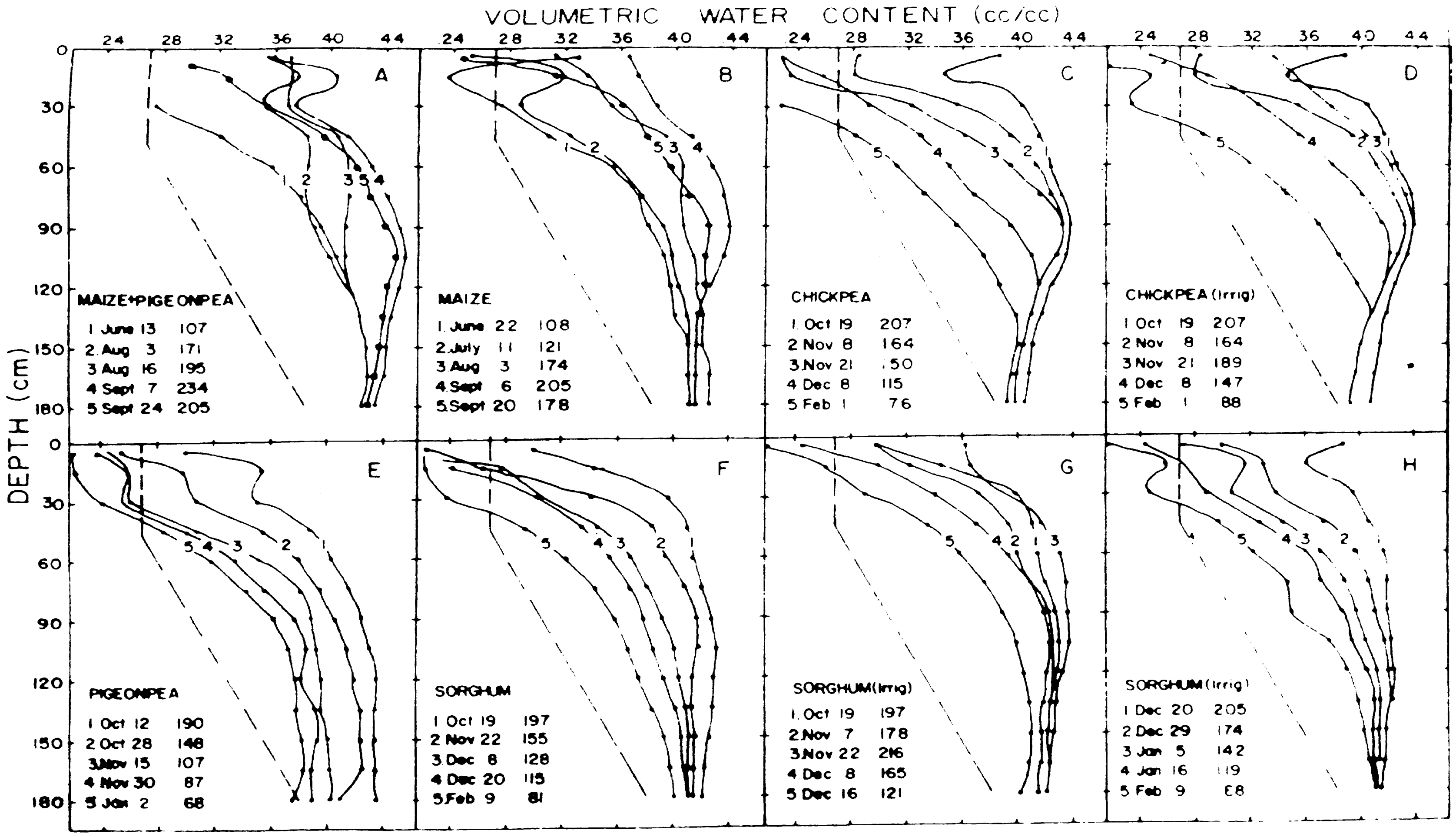


Figure 2. Time and depth patterns of profile water content during the rainy (A-B) and postrainy season (C-H).
(Environmental Physics Report, 1977-78)

Table 3. Millimeters of available water in six layers in a deep Vertisol during the postrainy season (Environmental Physics Report, 1977-78).

	Rainfed sorghum Depths (cm)							Irrigated sorghum 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
Layer capacity (mm)	30	50	45	36	29	24	214	30	50	45	36	29	24	214
19 Oct	23	41	30	33	25	21	181	23	41	30	33	25	21	181
07 Nov	20	35	35	31	23	18	162	20	35	35	31	23	18	162
17 Nov*								10	30	34	29	22	17	142
18 Nov†								30	50	45	36	29	24	214
22 Nov	5	28	34	29	22	16	134	32	42	43	36	26	21	200
08 Dec	4	18	25	23	19	15	104	4	27	34	31	26	18	140
16 Dec	2	12	19	18	14	12	77	0	14	23	22	19	13	91
19 Dec$^{\theta}$								0	8	19	19	16	11	72
20 Dec								34	41	39	31	25	19	189
29 Dec	4	5	18	18	15	14	74	24	27	34	29	24	18	156
05 Jan	-2	1	14	13	12	10	50	17	18	27	25	22	17	126
09 Jan								22	20	25	23	21	17	128
16 Jan	2	3	13	12	10	8	48	1	12	22	21	20	16	92
09 Feb	-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

Irrigation on Nov 18 and Dec 19

Total rain during season 72 mm

*Computed as 10/15 of Nov 7-22 loss from rainfed plots

†Assumed full capacity after Nov 18 irrigation

$^{\theta}$Computed as 11/8 of Dec 8-16 change

Table 4. Profile water use by pigeonpea during postrainy season from a deep Vertisol (Environmental Physics Report, 1977-78).

		DEPTH (Cm)						
	da	0-22	22-52	52-82	82-112	112-142	142-187	Total
				Millimeters				
24 Sep to 12 Oct	18	27	13	4	4	2	0	50
12 Oct to 28 Oct	16	18	11	7	4	3	4	47
28 Oct to 15 Nov	18	23	11	7	7	8	9	65
15 Nov to 30 Nov	15	6	3	5	3	3	6	24
30 Nov to 02 Jan	33	1	5	5	4	2	4	23
Seasonal total	100	75	43	28	22	18	23	209

The time and depth curves of profile water depletion were used to compute the rates of water extraction by roots. During periods of monotonic profile depletion such extraction rates are interpreted as the 'de facto' root distribution of the crop. Seasonal changes in root extraction rates of pigeonpea from the deep Vertisol are shown in Figure 3. Also shown are the changes in fractional available water at various depths in the profile.

The seasonal progression in depth and time of the water extraction rate by roots of pigeonpea shows that in the 0-22 cm layer the rate of water extraction remained greater than 0.022 mm of water per cm of soil per day (mm/cm/da) until the end of November even though the average fractional available water content of the 0-22 cm layer was low for each of the five periods. This suggests that the layer was well ramified by roots which were able (i) to exploit quickly and effectively the short-term increases in water in the 0-22 cm layer resulting from the small showers during those periods and (ii) to effectively extract water down to the -15 bars.

The vertical distribution of extraction rates for the October 12-28 period (Fig. 3B) is believed to give a realistic picture of the root distribution of the pigeonpea crop since at that time the profile was well supplied with water at all depths, hence the extraction rates should have reflected rooting density. At depths from 12 to 112 cm there was a gradual decline with time in extraction rates corresponding to the decline in fractional available water. The relative importance of extraction at depths below 142 cm increased as the rates in the upper layers declined.

The changes in the depth pattern of water extraction by rainfed sorghum are given in Figure 4 A-E. Early in the season extraction rates were low and largely confined to the upper three layers (Fig. 4A). As the crop developed and the surface layer dried, the rates of extraction in the 22-142 cm layers increased progressively (Fig. 4B-C). Later in the season the rates declined and the relative contribution of the upper layers fell while that of the profile below 112 cm increased (Fig. 4D-E). The integrated values for the entire season (Fig. 4F) show that all layers of the 187 cm profile contributed significantly to meeting the water requirement of the unirrigated sorghum crop. Recharging the profile by irrigations on 18 November and 19 December resulted in continuation of high extraction rates in the upper soil layers (Fig. 5).

The time and depth patterns of root extraction rates for unirrigated chickpea presented in Figure 6 A-C show the early season concentration of water use from the upper soil layers. Mid-season usage was concentrated in the 22-112 cm layers. As the upper layers were depleted the zone of maximum extraction moved downward with significant use below 112 cm in December. The November irrigation enabled the chickpea to sustain high rates of extraction from the 0-22 and 22-52 cm layers into early December (Fig. 6E) as shown by the relatively higher extraction rates in the upper layers.

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 7. Both crops were sown in mid-October. The rainfed and irrigated plots were treated alike prior to the profile-recharging irrigation applied on 19 November. The curves clearly show that total amount of water used and the position in the profile from which it was

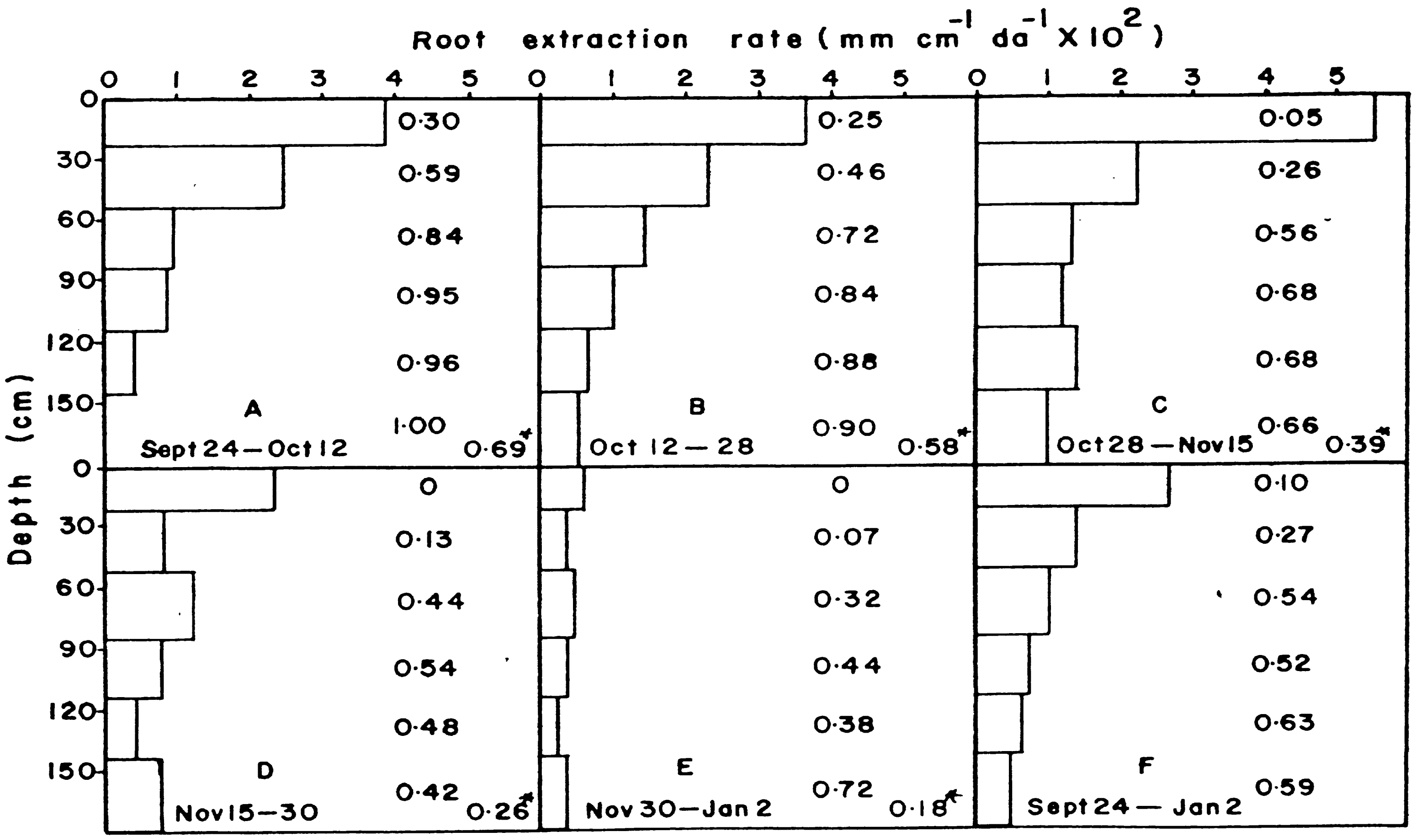


Figure 3. Root extraction rates by pigeonpeas and fractional available moisture for six layers of a deep Vertisol. (Environmental Physics Report, 1977-78).

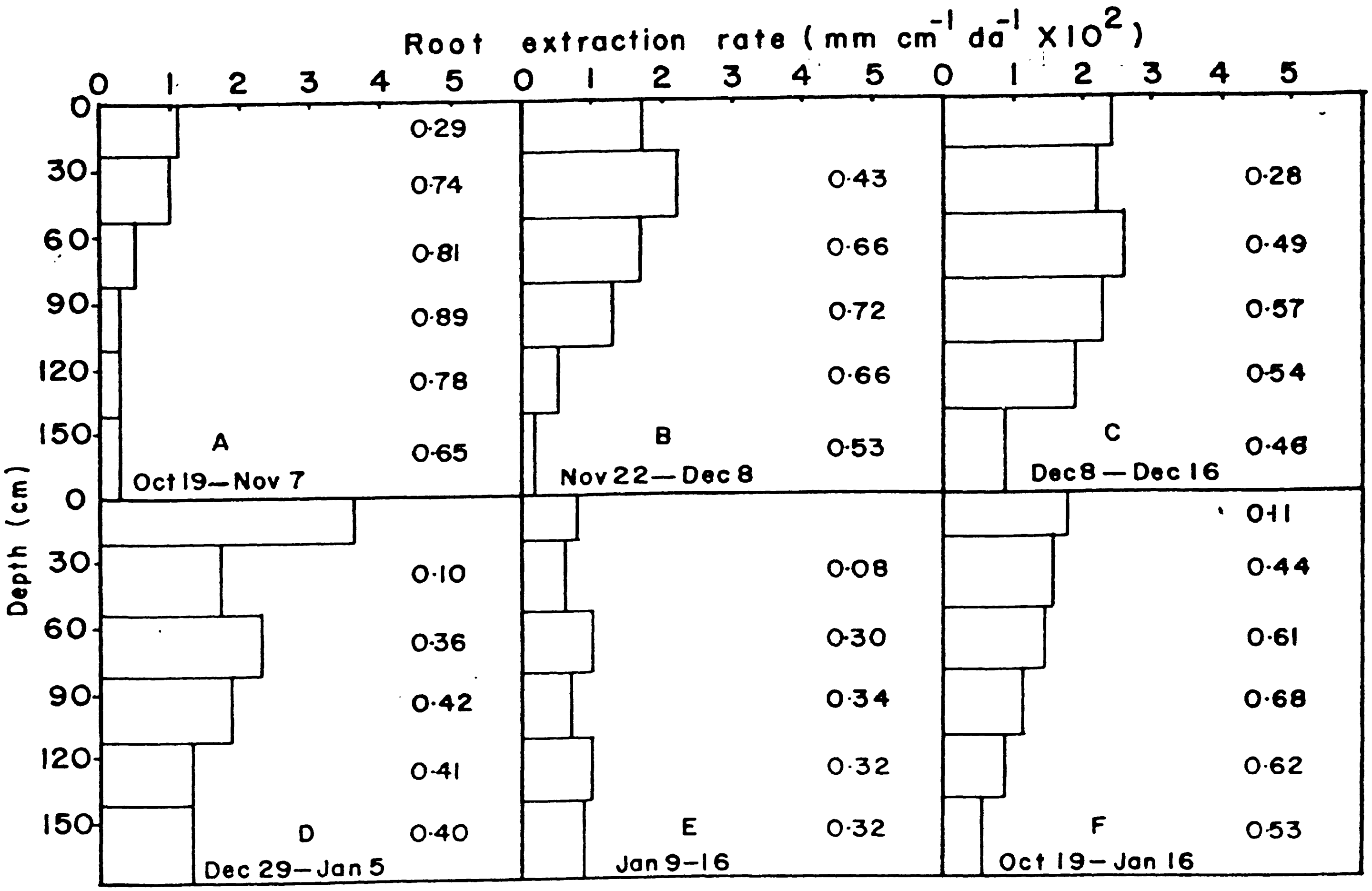


Figure 4. Root extraction rates by rainfed sorghum and fractional available moisture for six layers, of a deep Vertisol. (Environmental Physics Report, 1977-78).

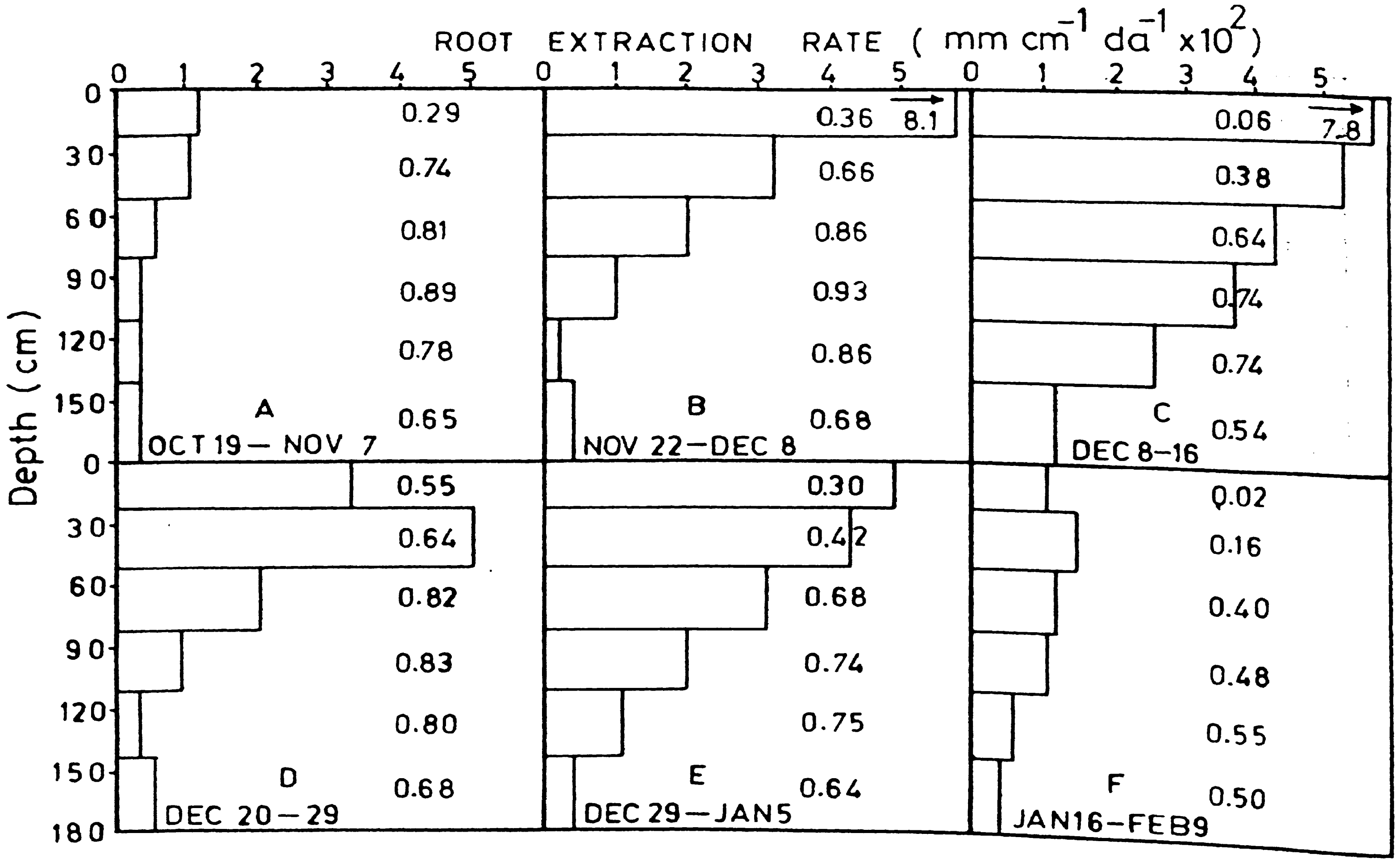


Figure 5. Root extraction rates by irrigated sorghum and fractional available moisture for six layers of a deep Vertisol. (Environmental Physics Report, 1977-78).

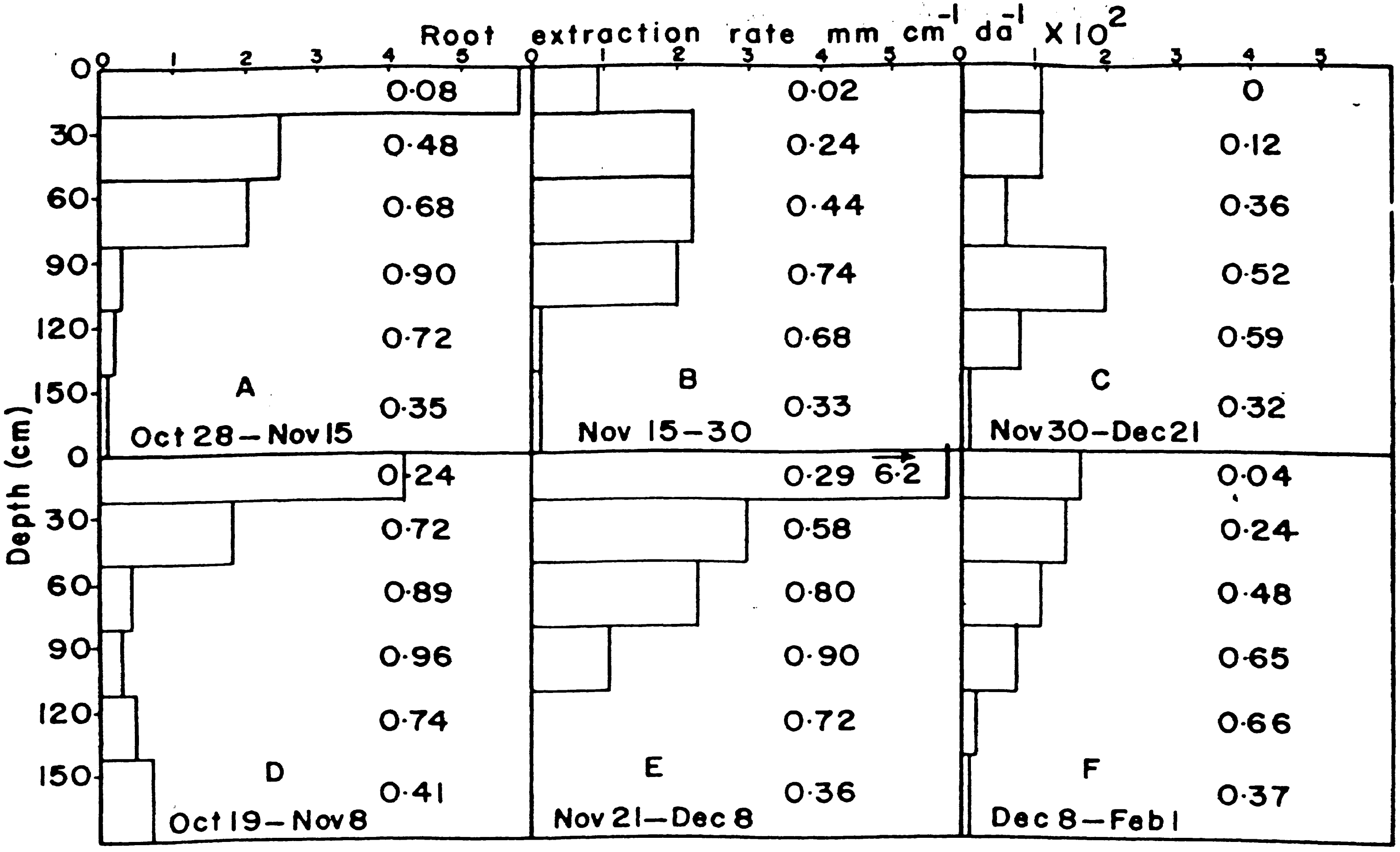


Figure 6. Root extraction rates by unirrigated (A-C) and irrigated (D-F) chickpeas from six layers of a deep Vertisol. (Environmental Physics Report, 1977-78).

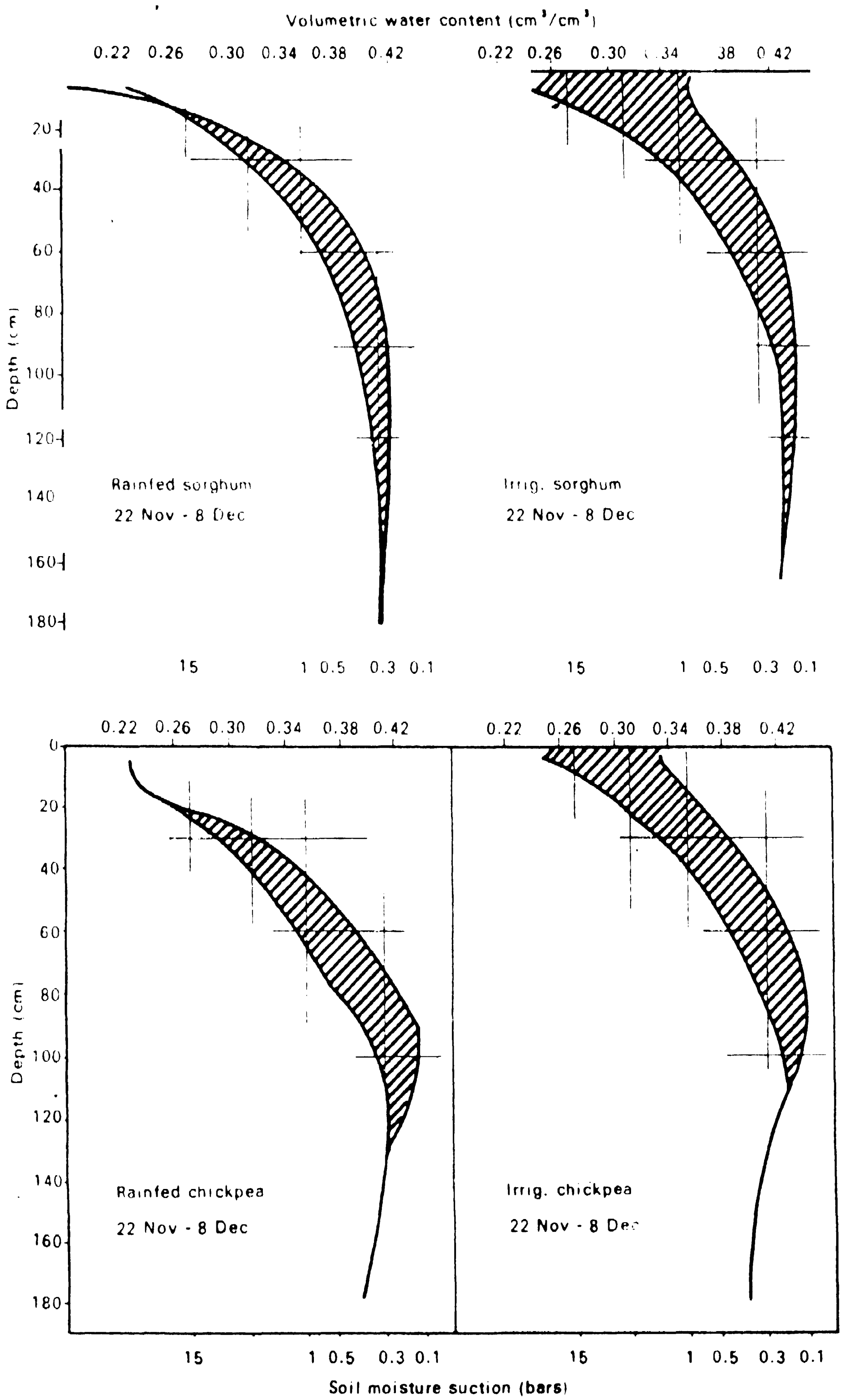


Figure 7. *Water-extraction profiles of rainfed and irrigated sorghum and chickpeas on a deep Vertisol.* (Russell, 1978).

extracted during the 16-day period were each quite different for the rainfed and irrigated crops. Since it is reasonable to assume that in plots the root system of the rainfed and irrigated crops was the same, at the time of the first irrigation the subsequent differences in water-uptake rates can be attributed to the greater depletion and the lower soil water potential or available soil moisture that existed in the upper parts of the profile in the rainfed plots.

ii) Profile water use by sorghum on an Alfisol: At the beginning of the postrainy season the 127 cm profile contained 115 cm of available water. This represented 87% of its capacity. Profile moisture depletion by the irrigated sorghum was confined to the top 90 cm with the major amount occurring from the top 52 cm of soil profile (Fig. 8).

Of the total depletion 44% and 39% were from the 0 to 22 and 22 to 52 cm layers, respectively, during the period from 15 December to 18 January. Appreciable depletion from layers below 52 cm was observed during January. This amounted to 13% of total from each of the 52 to 82 and 82 to 127 cm layers.

In contrast to the irrigated sorghum rainfed sorghum extracted relatively more water from the subsoil during the 16 November to 18 January period. Depletion from 0 to 22, 22 to 52, 52 to 82, and 82 to 127 cm layers were 38, 31, 16, and 14 percent respectively. With drying of the top soil, the contribution of 82 to 127 cm layer to the total transpiration during the 28 December to 18 January period increased to 30%.

iii) Water use by pearl millet on an Alfisol: Figure 9 shows the changes in volumetric water content with depth and time for the rainfed and irrigated millet crops. The curves indicate that the rainfed crop removed water progressively with depth and time to a depth of one meter during the first six weeks of growth at which time the plant extractable moisture was more than 80% depleted to a depth of 60 cm. Subsequent water use was confined to the 60 to 150 cm depth and essentially ceased two weeks later. The irrigated crop used the profile 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 and rainfed plots were similar. Profile water extraction by the irrigated crop continued for four weeks after the date when it ceased in the unirrigated plots.

The progressive depletion of the profile water is clearly shown in Figure 10 by the changes in capillary potential with time at various depths in the unirrigated plot. These data also show that root extraction essentially ceased by 10 December, eight weeks after sowing. At that time the potential at 30 and 45 cm had reached -15 bars. The continued fall in potential at 15 cm beyond -15 bars is attributed to evaporative moisture loss. It is concluded that the number of roots at depths below 50 cm were insufficient to withdraw water at the rate needed to maintain the millet crop which ceased to transpire and grow even though the capillary potential at 60 and 75 cm and presumably at deeper depths was above the wilting point.

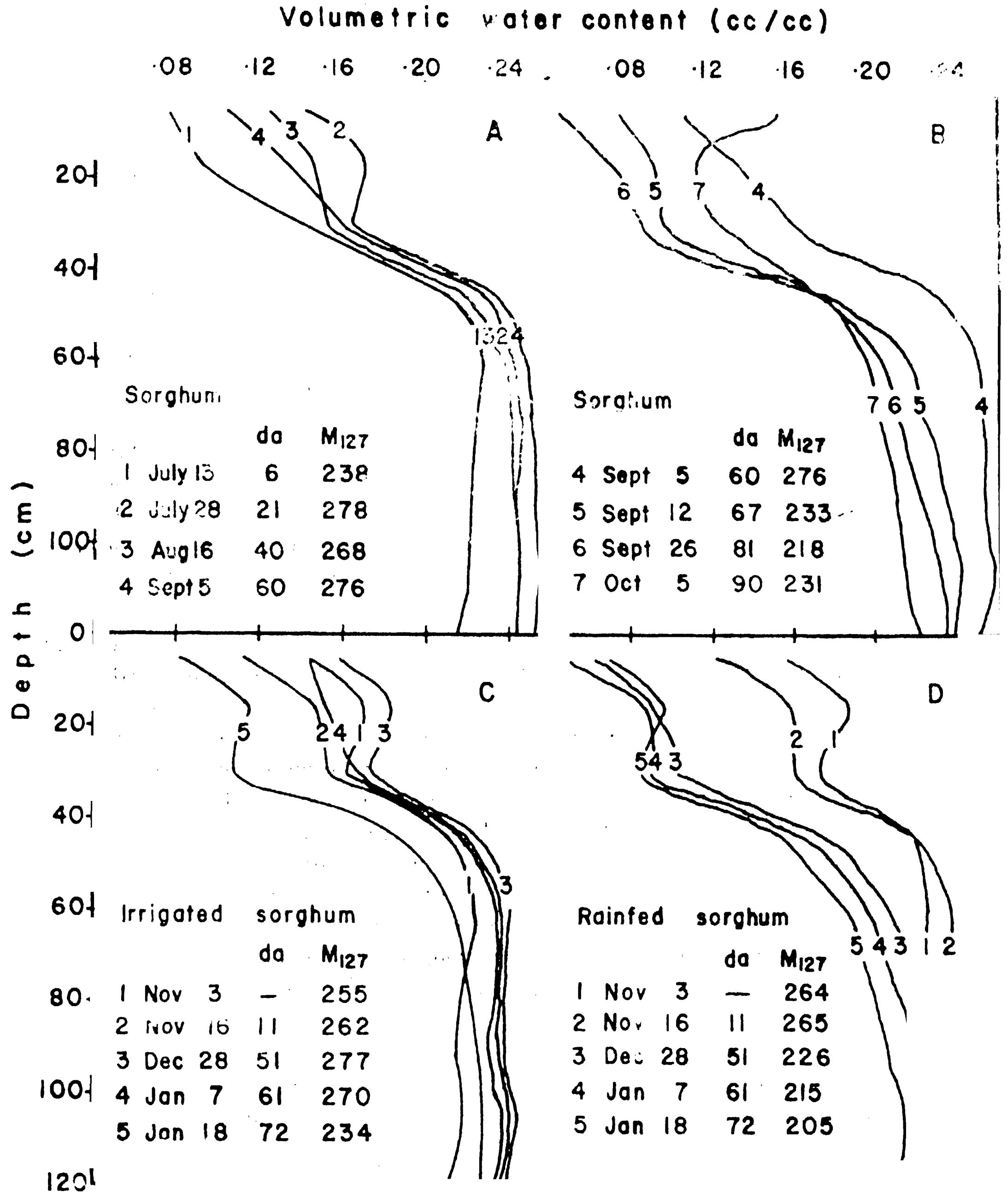


Figure 8. Soil moisture profiles under sorghum on an Alfisol during the rainy (A & B) and postrainy (C & D) seasons. (Environmental Physics Report, 1977-78).

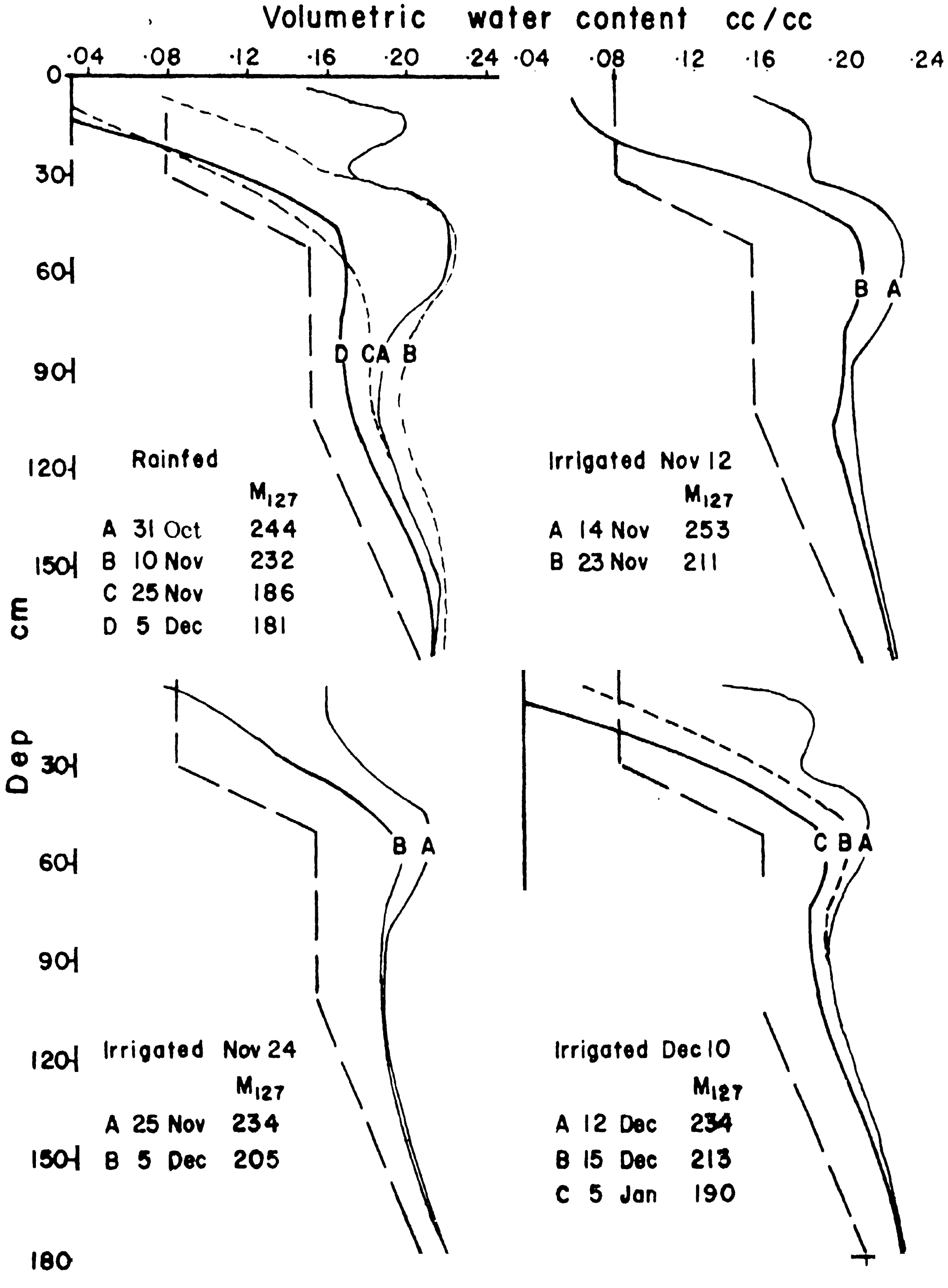
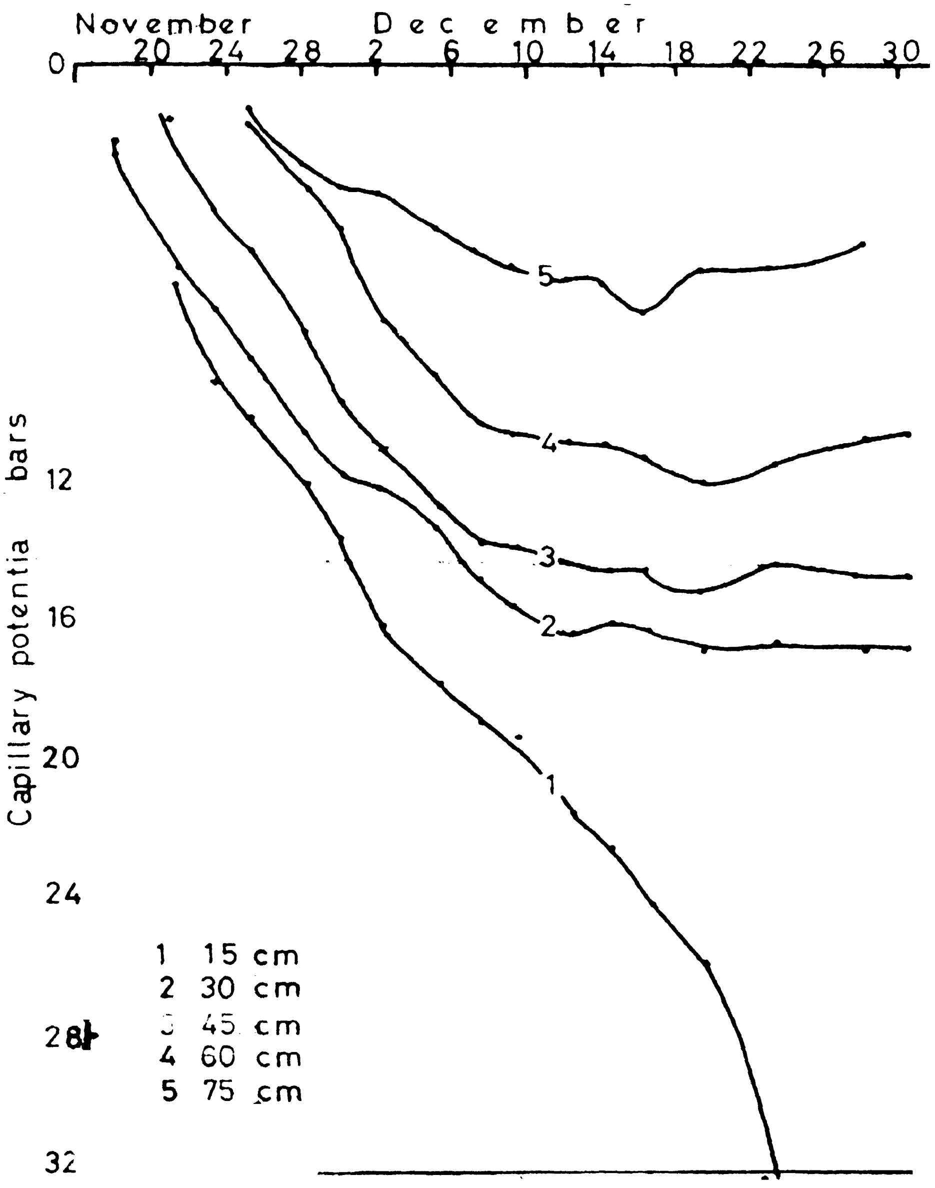


Figure 9. Moisture profiles of rainfed and irrigated pearl millet on an Alfisol. (Environmental Physics Report, 1977-78).



Capillary potential changes during profile depletion by pearl millet on an Alfisol

Figure 10. Capillary potentials under rainfed pearl millet on an Alfisol (Environmental Physics Report, 1977-78).

The rates of water extraction from various profile positions computed from the soil moisture profile curves for the irrigated millet crop are shown in Figure 11. The data on root density are also shown. 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.

Changes in available moisture at four depths in the irrigated plots are shown in Table 5. The 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 transpired 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 factors (CUF). The 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 82 cm in this Alfisol profile.

iv) Profile water dynamics in uncropped Vertisols and Alfisols: The progressive recharging of the deep Vertisol profile during the 1977 rainy season is clearly shown in Figure 12. During the 85 day period from 14 June to 7 September there was a net accretion of 133 mm in the 0 to 187 cm profile. During this period 466 mm of rain fell in well distributed showers which caused only 7 mm of runoff. Evaporation from the soil surface during the 85 days was 240 mm. Drainage beyond 187 cm, computed as the residual in the water balance equation, was 86 mm. Thus for the fallow deep Vertisol during the 1977 rainy season about half (52%) of the rain was lost by evaporation and one-fifth by drainage beyond 187 cm (18%) and surface runoff (2%); hence slightly less than three-tenths (28%) was retained in the 187 cm profile which was fully recharged by early September.

It is important to note that the distribution of losses and profile accretion is highly dependent on the number, size, intensity, and distribution in time of the seasonal rainfall. Had the same 466 mm of rain occurred in a different pattern of size, timing, and intensities the amounts lost by runoff, evaporation and drainage and perhaps the amount retained by the profile would have been quite different.

During the postrainy season the uncropped deep Vertisol lost water as shown in Figure 13. About 60 mm of rain fell during the last days of September and the firs week of October. This is shown by the moisture profile below 30 cm which on 6 October was well above field capacity. Consequently nearly 60 mm of water drained beyond 187 cm in the next 11 days. This is supported by the tensiometer data discussed below which showed large downward acting hydraulic gradients in the profile during that period. The small rains that occurred after 6 October were retained by the upper 20 cm of the profile from which they were quickly lost by evaporation. Thus the profile showed a continuous slow loss of water at increasing depths during the next 6 months as a consequence of evaporative loss from the soil surface.

Table 5. Seasonal changes in available water (mm) in four layers of an Alfisol under irrigated pearl millet (Russell, 1978).

	Depths					CU
	0-22	22-52	52-82	82-127	0-127	
31 October	22	28	18	16	84	0
10 November	4	25	20	21	70	14
12*	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
05 December	3	15	12	14	44	84
10+	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
05 January	0	12	8	14	34	129
Seasonal use	75	39	11	4		129
Layer capacity	26	33	20	27	106	
C U F	2.9	1.2	0.55	0.15		

CU	Cumulative Use,mm
CUF	Capacity Use Factor
*	Extrapolated from 31 Oct to 10 Nov losses
+	Extrapolated from 25 Nov to 05 Dec losses

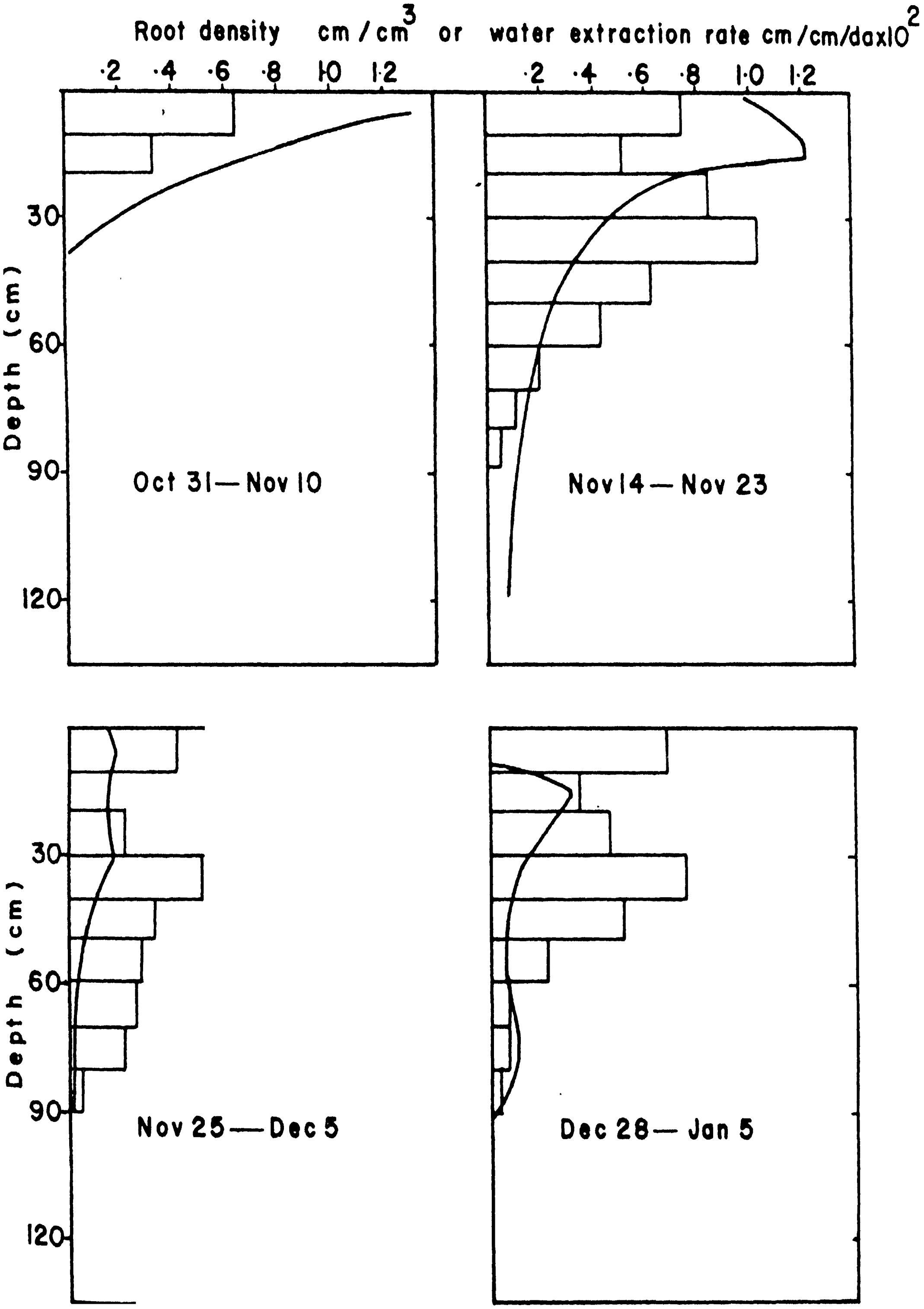


Figure 11. Root densities (bars) and water extraction rates (lines) of irrigated pearl millet on an Alfisol. (Environmental Physics Report, 1977-78).

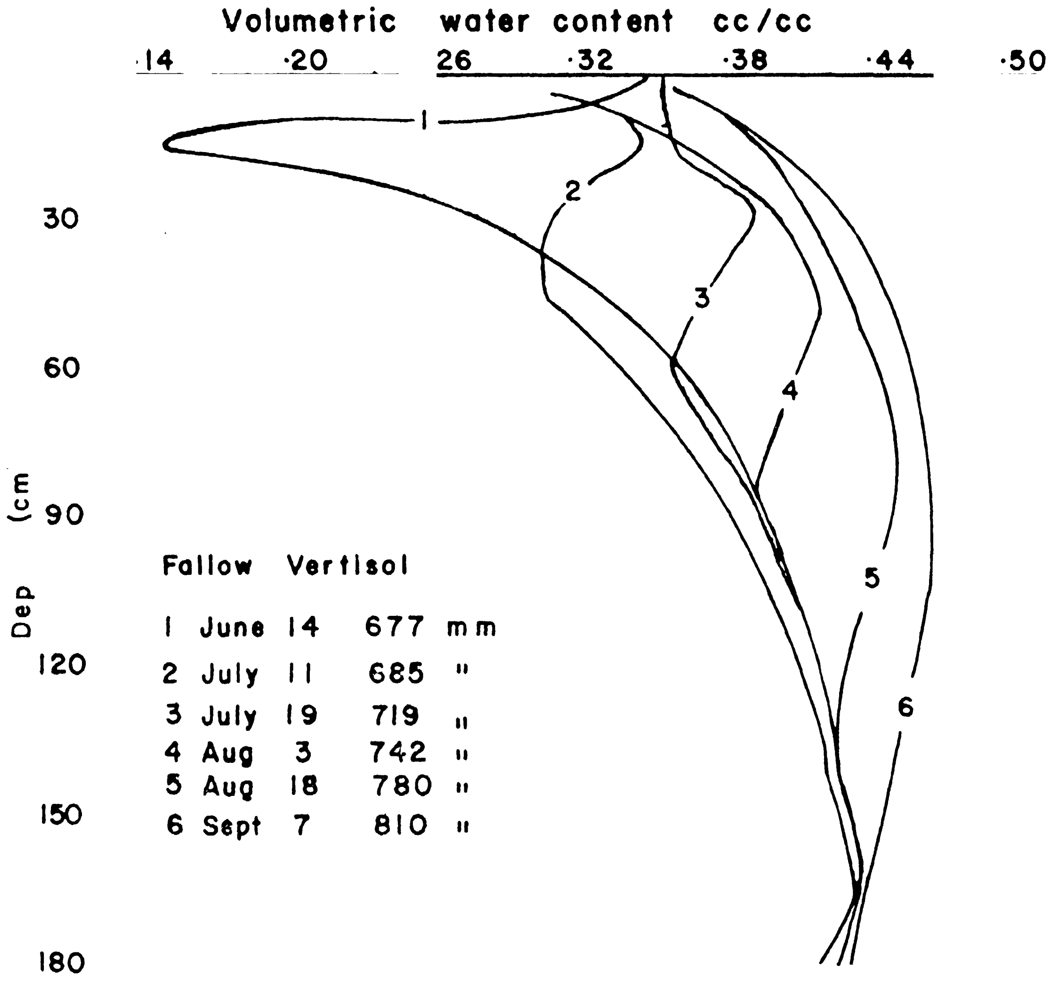


Figure 12.Moisture profiles of an uncropped deep Vertisol durin the rainy season (Environmental Physics Report, 1977-

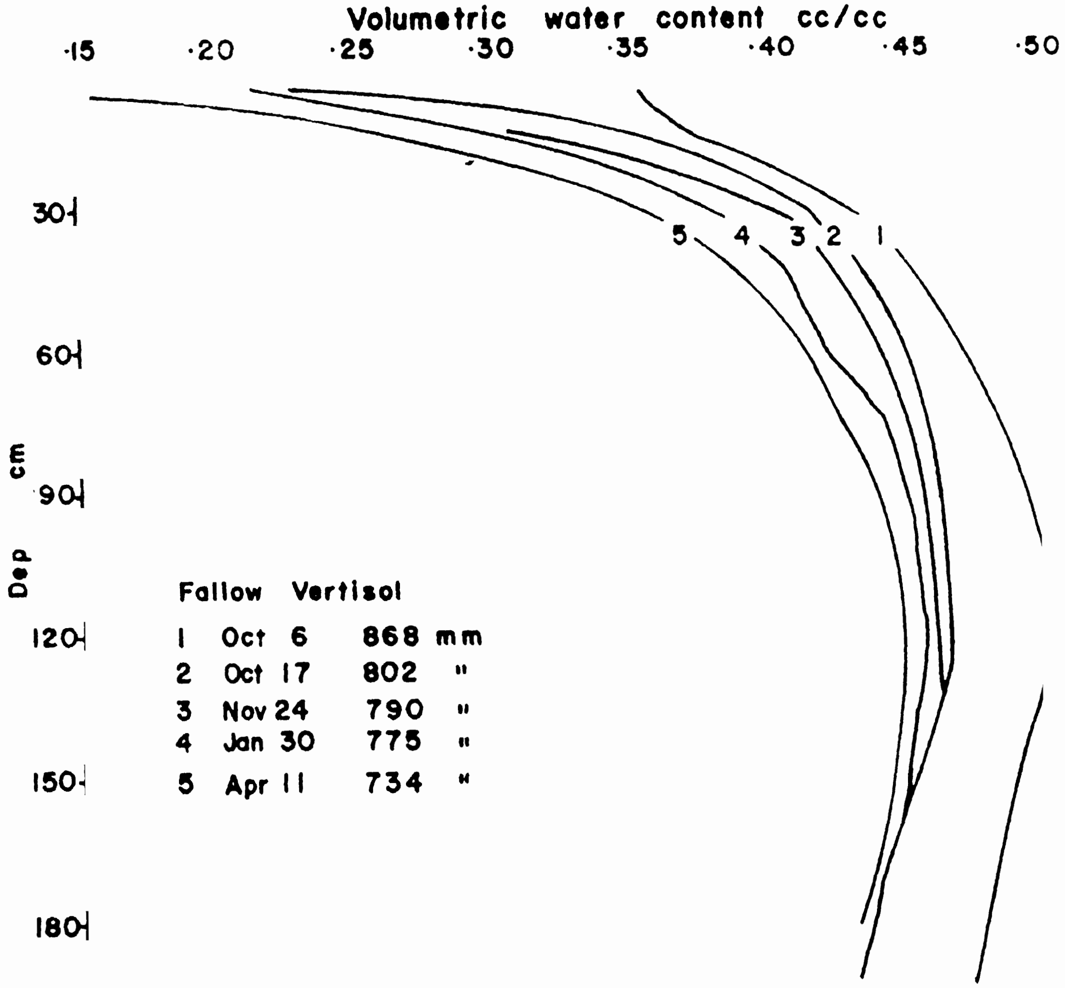


Figure 13. Moisture profiles of an uncropped deep Vertisol during the postrainy season (Environmental Physics Report, 1977-78).

The changes in water content at different depths in the Vertisol profile during the rainy season recharging and postrainy season depletion are shown in Figure 14. It is clear that when the moisture is lost only by evaporation or drainage, the amplitude of the annual change decreases with depth. In the upper 30 cm of the profile the recharging and depletion cycle is repeated many times depending on the seasonal distribution of rains. The frequency and amplitude of such changes are inversely related to depths; hence below 30 or perhaps 50 cm of the recharge and depletion occurs with an annual periodicity.

The changes in profile water content of the fallow deep Alfisol during the rainy and postrainy seasons are shown in Figure 15 and 16. Because the first data were not taken until 13 July following the late June rains which amounted to more on 120 mm, the size of the seasonal recharge in the deep Alfisol was only about 50 mm. It is estimated that the profile accretion would have been at least twice that amount if the profile water content had been measured prior to the early season rains. The general pattern of recharge and postrainy season depletion in the deep Alfisol was similar to that in the deep Vertisol discussed above. At depths below 30 cm recharge and depletion occurred on an annual basis whereas in the upper 30 cm the process occurred repeatedly with a periodicity determined by depth and by the size and frequency of the rains.

From the above data it is clear that Alfisols and Vertisols differ in various physical characteristics that affect the root distribution of crops in these two soil groups. In a given soil, differences in root distribution of crops have been observed. The amount and rate of water extraction by roots through the season has been followed using profile moisture curves and related to root distribution in a soil. For example, in the 1977-78 postrainy season pigeonpea depleted more subsoil water as compared to chickpea and sorghum on a Vertisol. This indicates that pigeonpea has more root density in the Vertisol subsoil as compared to chickpea and sorghum. In addition to root distribution, the availability of water in the soil profile also affect profile water depletion. In Vertisol, rainfed chickpea depleted more water from the subsoil compared to irrigated chickpea for the selected period of crop growth. Similar trends in profile water depletion were obtained when rainfed sorghum was compared to irrigated sorghum. Similarly in Alfisol, water depletion by rainfed pearl millet from the subsoil was increased due to water stress in the top soil layers. Whereas in case of irrigated pearl millet water depletion was confined to the top layers until the stress was encouraged by discontinuing irrigation.

Under sufficient soil water availability, water extraction rates of crops corresponded to their root density distribution in the soil profile as it was clearly shown in case of pearl millet. These extraction rates decreased with the decrease in the fractional available water. This indicates that when soil profile is well supplied with water, the water extraction rates could be interpreted as 'de facto' root distribution of the crop.

In Alfisols top layers of the soil profile contribute relatively more to the total crop water use than subsoil layers as indicated by their capacity use factors. Whereas in Vertisols, the subsoil layers contributed relatively more to the total crop water use due to higher water availability and greater rooting density in the Vertisol subsoil than in the Alfisols subsoil.

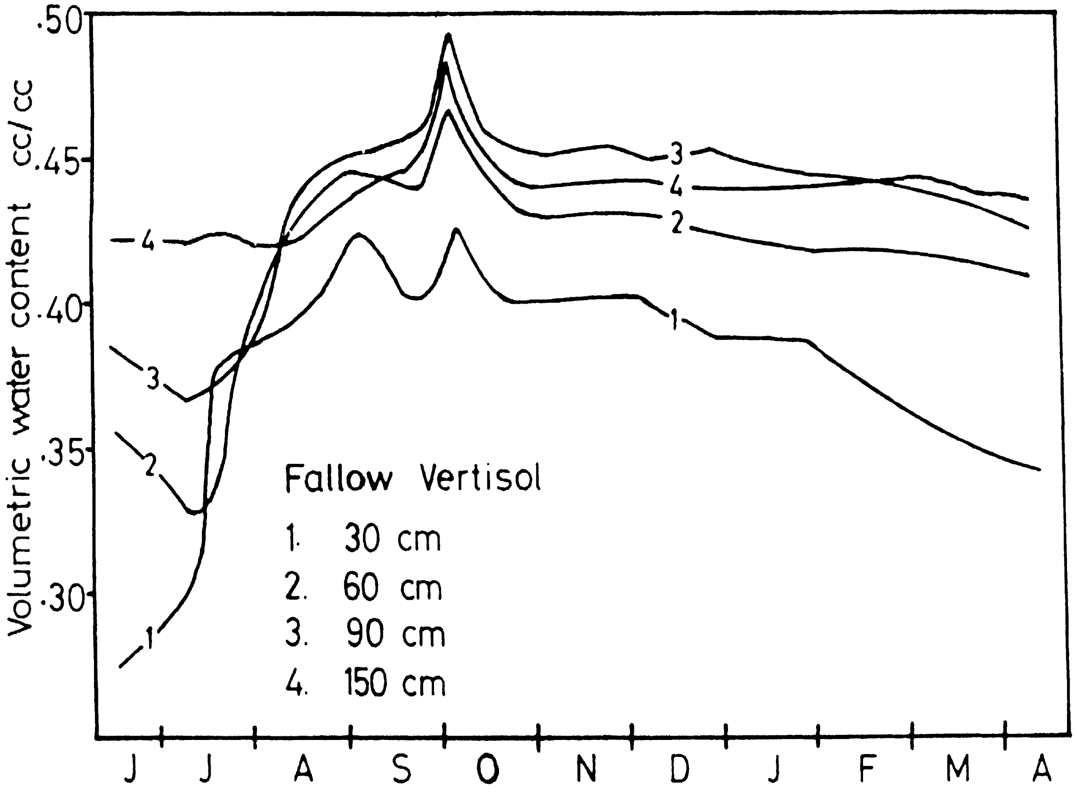


Figure 14. Seasonal water content at four depths in a deep Vertisol. (Environmental Physics Report, 1977-78).

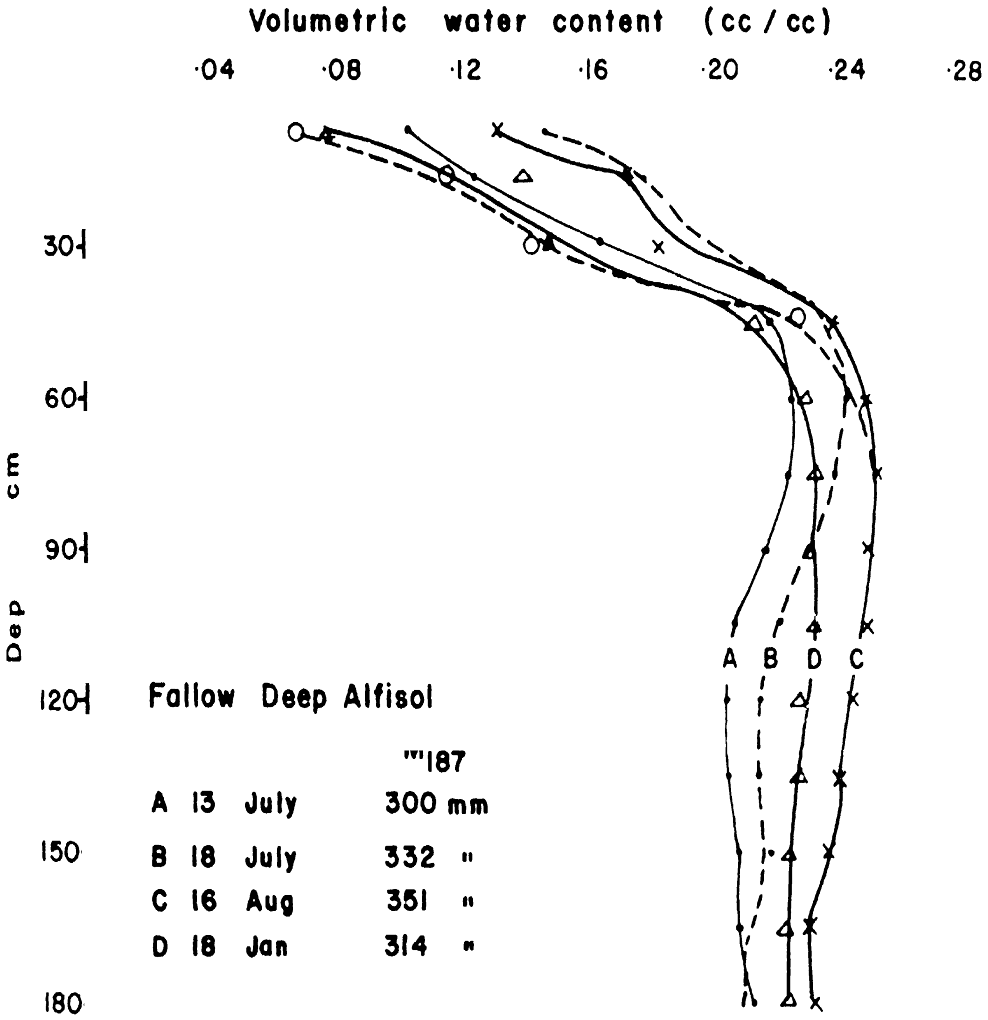


Figure 15. Seasonal changes in moisture profiles of an uncropped deep Alfisol (Environmental Physics Report, 1977-78).

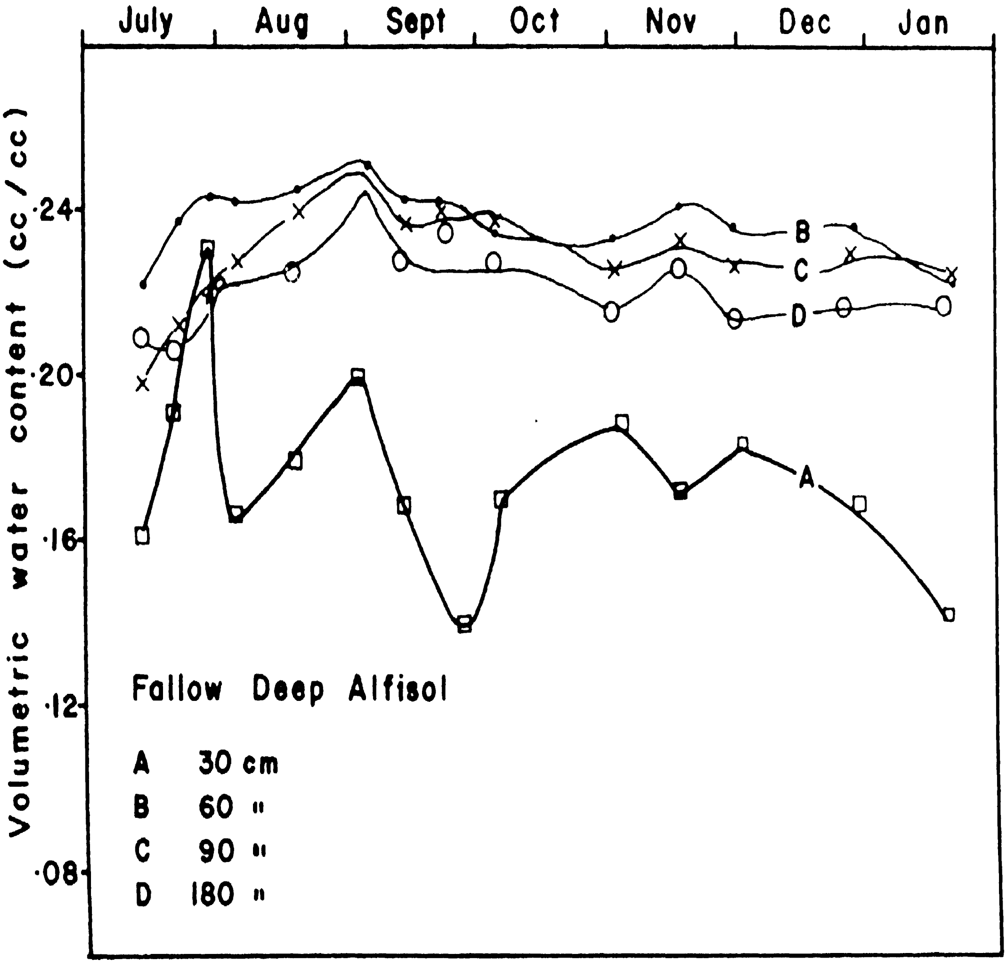


Figure 16. Seasonal changes in water content at four depths in an uncropped deep Alfisol. (Environmental Physics Report, 1977-78).

Table 6. Water balance components for maize/pigeonpea intercrop for 10 periods during the rainy and postrainy seasons in a deep Vertisol (Sardar Singh and M.B. Russell, 1980).

Calender period	Days	P	Eo	E*	ΔM	E	R	D	Tm	Te
					(mm)					
BW1 1977-78										
13 Jun-08 Jul	25	120	187	86	11	84			25	4
08 Jul-03 Aug	26	130	144	91	53	64			13	43
03 Aug-16 Aug	13	92	60	27	24	9			59	39
16 Aug-07 Sep	22	123	33	39	39	10			74	62
07 Sep-24 Sep	17	1	99	15	-45	5			41	50
Total	103	466	523	258	82	172			212	198
24 Sep-12 Oct	18	62	82	43	+ 1	22			39	41
12 Oct-28 Oct	16	12	81	28	-42	11			43	47
28 Oct-15 Nov	18	22	98	24	-48	6			64	74
15 Nov-30 Nov	15	16	61	8	-22	2			26	46
30 Nov-02 Jan	33	2	149	5	-24	2			24	90
Total	100	114	471	108	-135					
Grand Total	203	580	994	366	-53	215			408	496
Fraction of rainfall				0.63		0.37			0.70	
BW3 1977-78										
22 Jun-14 Jul	22	61	164	59	9	44	2		24	41
14 Jul-01 Aug	18	129	89	62	68	19			42	61
01 Aug-18 Aug	17	94	85	30	12	3	2	14	77	76
18 Aug-08 Sep	21	124	76	55	40	14			56	57
08 Sep-22 Sep	14		82	11	25	4			21	52
Total	92	408	496	217	86	84	4	14	220	287
22 Sep-24 Oct	32	75	159	56	-37	11			101	127
24 Oct-09 Nov	16	17	88	17	-32	2			47	78
09 Nov-23 Nov	14	5	67	9	-35	2			38	54
23 Nov-07 Dec	14	8	57	4	-15	1			22	41
07 Dec-21 Jan	45	17	199	22	- 7	12			12	91
Total	121	122	570	108	-126	28			220	391
Grand Total	213	530	1066	325	-40	112	4	14	440	678
Fraction of rainfall				0.61		0.21		0.03	0.83	

P = rainfall
Eo = open pan evaporation
E* = potential soil evaporation
ΔM = change in profile moisture to 187 cm
E = soil evaporation
R = runoff
D = drainage beyond 187 cm calculated from water balance using open pan as ET
Tm = mass balance transpiration
Te = energy balance transpiration

Table 7. Seasonal water balances for several crops on a deep Vertisol (Russell, 1978; Sardar Singh and M.B. Russell, 1980).

Year	Plot	Crop	da	P	I	Eo	Δ M	E	R	D	Tm	Te
						Rainy season						
1977-78	1	Maize / Pigeonpea Int.	92	408	-	496	86	84	4	14	220	287
1977-78	BW-1	Maize / Pigeonpea Int.	103	466	-	573	82	172	-	-	212	198
1977-78	BW-1	Maize	103	466	-	573	84	174	-	-	208	194
1977-78	3	Maize	92	408	-	497	39	71	5	42	231	326
1977-78	4	Maize	90	408	-	484	62	66	3	36	241	319
1978-79	BW-1	Maize / Pigeonpea Int.	119	1006	-	627	142	210	272	124	246	-
1978-79	BW-3	Maize / Pigeonpea Int.	97	975		459	196	149	235	223	172	-
						Postrainy season						
1977-78	1	Pigeonpea	121	122	-	570	-126	28	-	-	220	391
1977-78	BW-1	Pigeonpea	100	104	-	471	-135	43	-	-	196	298
1977-78	3	Chickpea	105	47	-	503	-150	35	-	-	162	242
1977-78	BW-1	Chickpea	88	104	-	402	- 97	58	-	-	143	224
1977-78	4	Sorghum	115	72	-	547	-144	40	-	-	176	250
1977-78	3	Irrigated chickpea	105	47	67	503	-135	36	-	-	213	281
1977-78	4	Irrigated sorghum	115	72	165	547	-132	51	-	-	318	284
1978-79	BW-1	Pigeonpea	96	80	-	450	-136	44	-	30	141	
1978-79	BW-3	Pigeonpea	108	120	-	479	-184	101	-	-	203	

da = days
P = rainfall (mm)
I = irrigation (mm)
E_o = open pan evaporation (mm)
ΔM = change in profile moisture (mm)

E = soil evaporation (mm)
R = runoff (mm)
D = drainage beyond 187 cm (mm)
T_m = mass balance transpiration (mm)
T_e = energy balance transpiration (mm)

Table 8. Water balance of crops in rainy and postrainy season on Alfisols (Data taken from Environmental Physics Report, 1977-78).

Location	Crop	da	P	I	E_o	ΔM	E	R+D	T_m	T_e
					Rainy season					
ST-2	Sorghum	75	343	0	364	- 22	90	125	150	178
					Postrainy season					
ST-2	Sorghum	72	52	0	329	- 75		0	89	107
ST-2	Sorghum (Irrig.)	72	143	0	329	- 38	63	0	118	106
RW-1	Pearl millet	45	30	0	210	- 66	19	0	77	105
RW-1	Pearl millet (Irrig.)	52	25	0	240	-130	31	0	124	125

da = days
P = rainfall (mm)
I = irrigation (mm)
E_o = open pan evaporation (mm)
ΔM = change in profile moisture (mm)
E = soil evaporation (mm)
R+D = runoff plus drainage (mm)
T_m = mass balance transpiration (mm)
T_e = energy balance transpiration (mm)

Table 9. Yields and water use efficiencies of rainy and postrainy season crops grown on a deep Vertisol (Russell, 1978; Sardar Singh and M.B. Russell, 1980).

Year	Crop	Yield (q/ha)	T_m (mm)	AW (mm)	WUE-1* q/ha/cm	WUE-2* q/ha/cm	WUE-3* mm/mm
			Rainy season				
1977-78	Maize	32.9	231	542	1.31	0.61	0.46
1977-78	Maize	36.3	241	516	1.51	0.70	0.47
1977-78	Maize	39.8	208	565	1.67	0.62	0.37
1977-78	Maize + Pigeonpea	24.9	212	573	1.17	0.93	0.37
1977-78	Maize + Pigeonpea	23.2	220	540	1.05	0.43	0.41
1978-79	Maize + Pigeonpea	25.3	246	1140	1.03	0.22	0.22
			Postrainy season				
1977-78	Pigeonpea	25.0	220	300	1.14	0.83	0.73
1977-78	Pigeonpea	15.8	196	293	0.81	0.54	0.67
1977-78	Chickpea	14.2	143	155	0.78	0.61	0.77
1977-78	Chickpea	10.5	162	209	0.65	0.50	0.78
1977-78	Irrigated chickpea	11.4	212	321	0.54	0.36	0.66
1977-78	Sorghum	25.3	176	269	1.44	0.94	0.65
1977-78	Irrigated sorghum	54.9	318	434	1.73	1.26	0.73
1978-79	Pigeonpea	10.7	141	271	0.76	0.39	0.52

WUE-1* = Water use efficiency expressed as grain produced per unit of water transpired
WUE-2* = Water use efficiency expressed as grain produced per unit of seasonal available water
WUE-3* = Water use efficiency expressed as fraction of seasonal available water transpired
AW = Seasonal available water = M+P+I where M = available profile water to 187 cm at planting

profile water dynamics of medium-deep Vertisols, Vertic Inceptisols, and Alfisols. These soils will be studied in more detail in the next few years. We also do not have quantitative information on any aspect of soil water on sandy soils of Western Africa, an important region of SAT outside India. Exchange of such information between scientists working in the 2 continents could be useful. Nutrient balance and nutrient dynamics in SAT soils is another important area of research that need to be investigated. ICRISAT and IRAT, perhaps, could usefully collaborate in this area of research. In the years ahead water use studies in various cropping systems will be initiated in Alfisols and Vertisols to collect quantitative information of water use in relation to crop productivity that could help in crop modeling and in the transfer of technology to other SAT areas.

Note: The work reported in this paper has been under the leadership of Dr. M. B. Russell, at ICRISAT. Associated with him were Dr. Piara Singh and Dr. Sardar Singh. Dr. Russell was Consultant Soil Physicist.

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Appendix 1. Analytical Data of an Udic Rodustalf (Pedon 6) at Patancheru (A typical Alfisol)*

Horizon	Depth (cm)	Size class and particle diameter (mm)								Coarse fragments >2 mm %
		Total			Sand					
		Sand (2-0.05)	Silt (0.05-0.002)	Clay (<0.002)	Very coarse (2-1)	Coarse (1-0.5)	Medium (0.5-0.25)	Fine (0.25-0.1)	Very fine (0.1-0.05)	
		% of < 2 mm								
Ap	0-10	73.0	9.1	17.9	11.5	10.3	17.8	24.3	9.1	4
A12	10-20	72.5	9.1	18.4	9.7	10.8	17.8	24.6	9.6	6
B1	20-30	58.2	9.3	32.5	14.3	9.0	11.6	16.9	6.4	10
B21t	30-49	56.9	8.6	34.5	11.1	8.4	13.1	17.2	7.1	8
B22t	49-102	53.1	7.4	39.5	30.0	6.5	6.3	6.7	3.6	37
B3	102-145	61.9	13.8	24.3	25.3	12.0	9.6	9.3	5.7	15

Horizon	pH (1:2.5) H_2O	Extractable bases					CEC NH4OAc
		Ca	Mg	Na	K	Sum	
		me/100 g					
Ap	6.5	5.8	2.0	0.1	0.3	8.2	8.1
A12	6.5	5.6	2.1	0.2	0.3	8.2	8.4
B1	6.7	10.8	2.9	0.2	0.2	14.1	14.6
B21t	6.7	11.0	3.1	0.2	0.2	14.5	15.1
B22t	7.8	14.3	3.4	0.3	0.2	18.2	17.0
B3	7.0	18.9	4.7	0.3	0.2	24.2	22.2

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*Data taken from Benchmark Soils of India (edited by R.S. Murty, L.R. Hirekerur, S.B. Deshpande, and B.V. Venkata Rao), published by the National Bureau of Soil Survey and Land Use Planning (ICAR), P.308-315.

Appendix 2. Analytical Data of a Typic Pellustert (Pedon 5) at Patancheru (A typical Vertisol)*

Horizon	Depth (cm)	Size class and particle diameter (mm)								Coarse fragments >2 mm %	Water retention	
		Total			Sand							
		Sand (2-0.05)	Silt (0.05-0.002)	Clay (<0.002)	Very coarse (2-1)	Coarse (1-0.5)	Medium (0.5-0.25)	Fine (0.25-0.1)	Very fine(0.1-0.05)		1/3-bar %	15-bar %
		% of < 2 mm										
Ap	0-20	23.5	22.8	53.7	4.0	2.2	4.3	8.6	4.4	6	31.2	13.4
A12	20-40	21.7	21.6	56.7	3.6	2.2	3.9	7.6	4.4	6	32.6	14.2
A13	40-60	19.5	22.1	58.4	4.4	2.0	3.1	6.2	3.8	6	-	-
A14	60-90	16.2	23.7	60.1	1.5	1.9	3.0	5.9	3.9	6	-	-
AC	90-130	11.6	21.0	67.4	1.0	1.1	2.1	4.3	3.1	7	34.6	17.2
C	130-180	12.9	20.4	66.7	1.2	1.5	2.1	3.9	3.2	9	34.2	16.7

Horizon	Organic carbon %	$CaCO_3$ equiv. %	pH (1:2.5) H_2O	Extractable bases					CEC NH4OAc	ESP	EC (1:2.5) mm hos/cm
				Ca	Mg	Na	K	Sum			
				me/100 g							
Ap	0.73	5.3	8.8	41.7	10.9	0.9	0.7	54.2	57.2	2	0.09
A12	0.54	7.4	9.2	37.5	14.7	5.3	0.6	58.1	58.5	9	0.09
A13	0.47	7.0	9.4	38.4	13.0	2.9	0.6	54.9	56.1	5	0.09
A14	0.39	6.3	9.4	34.1	16.4	7.8	0.6	58.9	60.0	13	0.18
AC	0.28	6.2	9.4	30.2	18.4	12.8	0.6	62.0	62.9	20	0.45
C	0.25	7.5	9.4	26.2	19.1	14.2	0.6	60.9	61.5	23	0.54

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*Data taken from Benchmark Soils of India (edited by R.S. Murty, L.R. Hirekerur, S.B. Deshpande, and B.V. Venkata Rao), published by the National Bureau of Soil Survey and Land Use Planning (ICAR), P.308-315.

CROP RESPONSE TO AVAILABLE WATER AND WATER REQUIREMENTS[1]

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SUMMARY

To increase and stabilize food production in the semi-arid tropics, improvement in the water use efficienceies of crops is essential. Understanding the nature of development of crop water deficits resulting from interactions between soil, plant and atmospheric factors, would assist in developing agronomic practices for increased water use efficiency. Several experiments have been conducted at ICRISAT during the postrainy-season to examine crop response to available water and water requirements. A holistic approach involving measurements of water transfer in the soil-plant-atmosphere continuum was adopted in these studies. Changes in the canopy physical environment and in plant parameters of water stress such as leaf water potential, stomatal conductance, leaf temperature, and transpiration due to water deficits were discussed. The relationship between water use and plant growth was described in terms of leaf area, dry matter,yield and yield components. The need to consider carefully the crop phenology in assessing the water deficit effects was emphasized. Water use and water use efficiency data collected for several crops/ cropping systems grown at ICRISAT Center were presented with special reference to their implications in improved farming systems.

1. INTRODUCTION

Most of the cropping in the semi-arid tropics (SAT) is and will continue to be under rainfed conditions. The SAT regions are characterized by a high climatic water demand and by a variable and erratic rainfall (Virmani and Sivakumar 1982). The problem essentially involves balancing or matching, over time, and discontinuous water supply with the continuous atmospheric evaporative demand. The resultant water stress, the intensity and duration of which varies from season to season, affects almost every physiological responses that are observed, and their relative importance in crop productivity, vary with species, soil type, nutrients and climate, but there are general features that can be identified and quantitatively modeled.

The objective of water response studies at ICRISAT is to understand the physical processes operating in the system and to measure in situ quantities of water involved, the rates at which transfers occur, and the quantitative effects of the system which controls them.

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Several experiments have been conducted at ICRISAT to examine the effect of water stress imposed at different phenological stages of crops such as sorghum, pearl millet, chickpea, groundnut and also intercropping systems like pearl millet/ groundnut, sorghum/millet etc. Review of all the experiments conducted and the discussion on each of the plant parameters measured in each of these experiments is beyond the scope of this paper. The purpose here is to discuss semi-quantitatively the effect of moisture stress on several soil and plant parameters.

2. APPROACH AND METHODOLOGIES ADOPTED

Recognition of the nature of development of water deficits lead us to believe that water transfer in the soil, plant, and the atmosphere should be monitered simultaneously. As the soil is dried, the soil water potential decreases and so does the soil hydraulic conductivity. Thus it is more difficult for plants to extract water (Gardner 1960) and, as a consequence, the plant water potential tends to decrease. This decrease may directly effect the physical aspects of some physiological processes. Under field conditions, several components (such as temperature, vapor-pressure deficit, wind speed, etc.) cause a decrease in the plant turgor pressure and a decrease in 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 influence the leaf temperature. In view of these effects, measurements in the soil, on the plants and their environment, are made in many of the experiments involving the study of water stress effects on crops grown at the ICRISAT Center.

In terms of water stress, the important season for our consideration is the postrainy-season during which the crops grow under residual soil moisture from the rainy season. Most of the moisture stress studies at ICRISAT are conducted during this season or the subsequent summer season because of near natural 'rain-out shelter' that this season provides for the crops (Table 1). Three of the ICRISAT mandate crops i.e., chickpea, pigeonpea, and groundnut are grown during the post-rainy-season . Also a substantial area in the Vertisol is sown to sorghum during the postrainy season. Understanding the profile moisture changes and the crop response to available soil water under these conditions is important to evolve strategies for soil and crop management in the SAT.

To study the crop response to available water, the methodologies adopted at ICRISAT involved one or more of the following techniques:

a) Creating different profile water regimes by giving 1, 2 or more supplemental irrigations at selected growth stages and comparing the crop performance against an unirrigated control.

b) Imposing a moisture stress gradient using a 'line source' method of water application similar to that described by Hanks et al. (1976). This technique uses standard sprinkler heads spaced at half the normal spacing along the irrigation line which produces a continuously decreasing rate of water

Table 1. Mean normal monthly rainfall, air temperature, relative humidity, and vapor pressure during the postrainy season at Hyderabad

Month	Mean Rainfall (mm)	Temperature (^{o}C) Max	Temperature (^{o}C) Min	Relative humidity (%)	Vapor pressure (mb)
October	71	30.3	19.8	73 (AM) 58 (PM)	23.2 (AM) 22.0 (PM)
November		28.7	16.0	68 (AM) 48 (PM)	18.6 (AM) 17.1 (PM)
December		27.8	13.4	71 (AM) 42 (PM)	15.9 (AM) 13.8 (PM)
January		28.6	14.6	79 (AM) 36 (PM)	16.3 (AM) 14.5 (PM)
February	10	31.2	16.7	64 (AM) 35 (PM)	16.1 (AM) 14.5 (PM)

application at right angle to the sprinkler line. The treatments normally involved creation of a different profile moisture stress of a selected duration at different stages of the crop. Comparison of the stress created at different stages to a control treatment irrigated at regular intervals yielded information on crop susceptibility to moisture stress at different stages.

c) Imposing moisture stress at selected phenological stages of the crop by withholding irrigation at that stage and releasing the moisture stress at all other stages by re-irrigating the crop. Comparison of the moisture stress treatment against a control treatment irrigated throughout the crop growing season provided information on the effect of moisture stress at selected growth stages.

d) In the case where the crop is grown on a soil with a receding profile moisture as in the postrainy-season, varying the date of planting so that the crop planted progressively late comes under an increasing level of profile moisture stress and creating different profile moisture regimes by giving one or more supplemental irrigations. Comparison of the crop performance across the planting dates and irrigation regimes provides information on water stress as well as temperature stress and the interaction between the two.

The measurements made in the moisture stress studies include time and depth measurements of soil water, seasonal changes in the leaf area index and distribution of dry matter in different plant parts, leaf water potential, stomatal conductance, leaf or canopy temperature, transpiration, air temperature, air vapor pressure deficit, net radiation, reflected radiation or albedo, soil temperature, and final yield and yield components. These measurements are made by an interdisciplinary team of scientists involving agroclimatologist, soil physicist, soil and water engineer, and plant physiologist.

3. FINDINGS

a) Effect of Water Stress on the Physical Environment of the Crop

i) Soil water: When the water supply to a crop is withheld, the soil begins to dry and the crop begins to show symptoms of drying or wilting as a consequence of reduction in the canopy transpiration. We have observed that the cumulative evaporation from the sorghum crop that was irrigated at 10 days interval was almost linearly related to cumulative potential evaporation as calculated by Penman (1970) method (Fig. 1). When irrigation was withheld in the early growing season, the evaporation was reduced almost immediately because the canopy growth at this stage was small, and a significant proportion of the evaporation from the irrigated crop came from the soil surface -- the soil surface of this unirrigated crop dried rapidly and evaporation from the soil surface decreased as a consequence. However, in a treatment where irrigation was withheld after the anthesis of the sorghum crop period evaporation continued at the maximum rate for sometime and then the rate declined. These data show that the

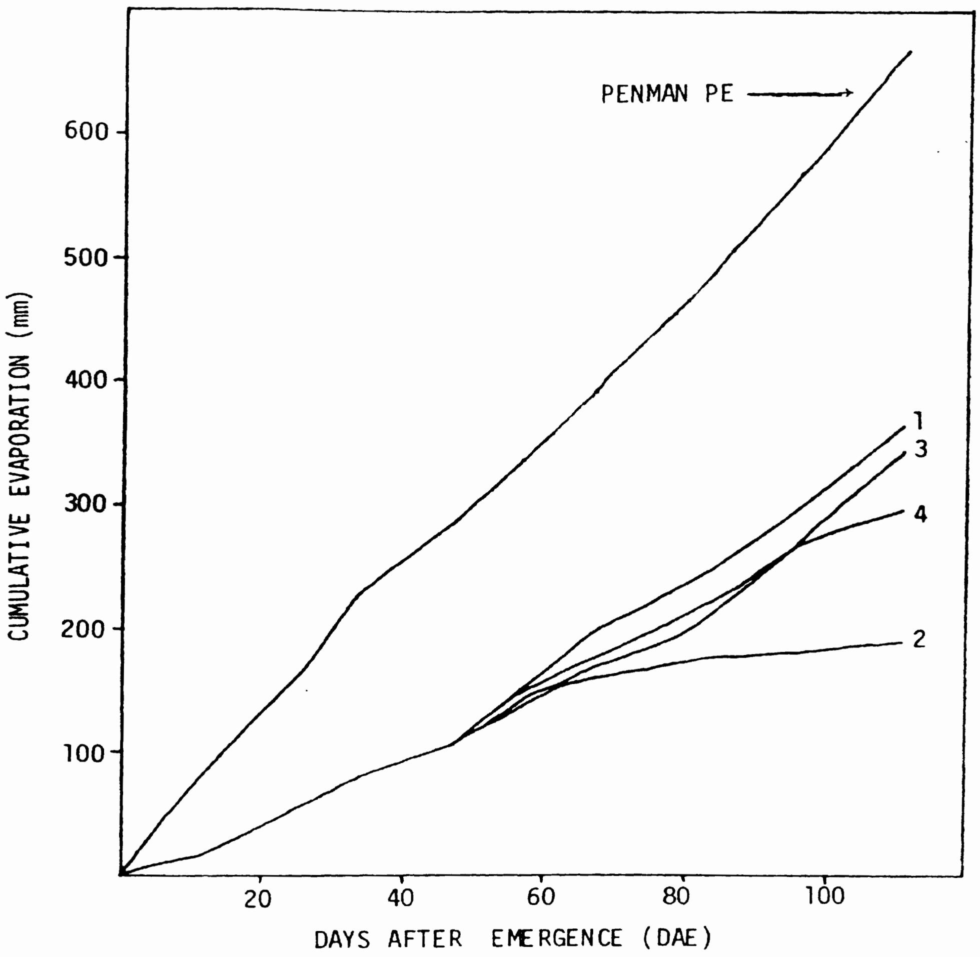

Figure 1. Cumulative water use from sorghum crop as compared to potential evaporation (Penman 1970). The treatments refer to: (1) Irrigated every 10 days, (2) Unirrigated after 35 DAE, (3) Unirrigated 35-65 DAE, and (4) Unirrigated after 65 DAE.

relative contribution of soil evaporation and the transpiration from the crop would have a significant effect on the canopy evapotranspiration. The amount of water extracted by the canopy will depend on the depth of rooting, and the soil characteristics.

The depth at which soil water is available to the plants is also a critical factor that would control the plant water status and the plant growth and development. For example, in an experiment which involved application of either 2 or 4 supplemental irrigations to a chickpea crop as opposed to no irrigations, it was observed that the timing and amount of water application results in a range of profile water depletions. Starting from about 50 days after planting, nonirrigated chickpea (treatment I_0) had little soil water available in the top 22 cm. In the next two layers down to a depth of 82 cm, rapid water extraction occurred up to about 80 days after planting leaving considerably smaller amounts of available soil water. Water extraction was comparatively low in the 82-112 cm soil layer and no water extraction was observed below this. Water extraction was higher in the irrigated chickpea crop because of the additional amounts of water supplemented to the crop. Changes in the available soil water in the treatment where two supplemental irrigations were applied show that chickpea could extract water up to 65 days after planting in the top 22 cm of soil. In the soil layers up to 82 cm depth, water was extracted at a faster rate compared to the I_0 treatment. Because of 4 supplemental irrigations given to the I_2 treatment, available soil water was higher in all soil layers down to a depth of 112 cm. Chickpea crop under I_0 treatment was under considerable soil moisture stress from 50-60 days after planting whereas I_2 treatment suffered from little moisture stress.

In the case of a sorghum crop grown on a deep Vertisol it was found that the sorghum crop could extract water from the profile in the treatment where supplemental irrigations were given till about 80 days after planting (Sivakumar et al. 1978). In the treatment receiving no supplemental irrigations, water extraction from the 0-22 cm soil layer stopped by about 33 days after planting. The data indicate that in a postrainy-season following a rainy-season with about 545 mm of rainfall, addition of even 19 cm of water would enable the crop to extract an additional 108 mm of water during the growing season.

ii) Soil temperature: Data that were collected on the variation in soil temperature at 10 cm depth in a sorghum crop showed that the soil temperature is the least in the treatment where water was applied at 10 days interval. A maximum soil temperature of about 31°C was recorded when no irrigations were given to the crop after the application of a differential water by means of a line source at 35 days after the emergence of the crop. All other water application regimes showed soil temperatures that were intermediate between the control treatment and the treatment where moisture stress was maximum. Soil temperature variations at 10 cm depth in chickpea crop showed that the maximum soil temperatures were recorded in the treatment where no supplemental water was applied to the chickpea crop in any of 4 planting dates i.e., 19 October, 4 November, 19 November, and 4 December. The minimum soil temperature of about 18°C was recorded in the treatment where the chickpea crop was sown on 4th of December and was given 4 supplemental irrigations at 30, 45, 60, and 75 days after planting.

iii) Radiation balance: Data collected on the interception of radiation by irrigated and unirrigated sorghum showed that the sorghum crop which was under moisture stress was not able to intercept radiation at the same level attained by the irrigated sorghum crop because of lower leaf area index and also leaf rolling. On a seasonal basis it was shown that the unirrigated crop intercepted about 20% less radiation as compared to the irrigated sorghum crop. Measurements of net radiation above the crop also showed that on a diurnal basis the irrigated sorghum crop intercepted about 31 langleys of net radiation that corresponded to approximately 0.5 mm of water. These data reflect the ability of the crop to extract more water from the soil in the irrigated treatment as compared to the nonirrigated moisture stress treatment.

The measurements of reflected radiation in an experiment where a groundnut crop was subjected to moisture stress at different phenological stages also showed that the albedo (percent of reflected radiation) was always more in the treatment where the groundnut crop was about 18 m from the line source as compared to the groundnut crop which was growing next to the line source. Under conditions of moisture stress the groundnut crop would show adaptations that would enable it to reduce the energy load on the crop by means of reflecting more light away from the canopy. In terms of the energy balance of the crop this would imply that the net radiation would also be lower in the case where the groundnut crop is under moisture stress. This observation was also true in the case of the sorghum crop that was grown under limited water supply.

b) Plant Parameters and Water Stress

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 are measured to characterize water stress in different studies at ICRISAT Center are: leaf water potential, stomatal resistance, leaf temperature, and transpiration.

i) Leaf water potential: According to Slatyer (1969), the level of water status in the plant and hence internal water deficit is influenced by two factors i.e., level of soil water status and diurnal lag of absorption behind transpiration.

We have adopted the pressure chamber technique for the measurement of leaf-water potential in chickpea. We found that 8 days after supplemental irrigation of 7 cm, irrigated chickpea plants were fairly turgid throughout the day, with a minimum leaf water potential of -7.5 bars at 1330 hrs (IST) compared with -10.5 bar for the unirrigated crop (Sivakumar and Virmani 1980). However, 33 days after the supplemental irrigation a minimum leaf-water potential of -24 bar was recorded at 1330 hrs for unirrigated chickpea against -18 bar for irrigated chickpea. Changes in the leaf-water potential corresponded closely with changes in the measured available soil water in the two treatments.

Under two supplemental irrigations measuring 8 and 11 cm, we measured irrigated sorghum leaf water potentials which never exceeded -13 bars at any time during the day while unirrigated sorghum showed leaf-water potentials lower than -15 bars from 1000 to 1700 hrs IST. On a seasonal basis the unirrigated sorghum extracted 213 mm of water as compared to 321 mm of water extracted by the irrigated sorghum (Sivakumar et al. 1978).

Seasonal changes in the leaf-water potential measured at regular intervals throughout the growing season also showed that better water use in the case of sorghum grown close to the line source was closely related to the ability of the sorghum plant to maintain a higher leaf-water potential (Sivakumar et al. 1981). It should be mentioned however that plant-water potential does not depend solely on the soil water but also on the plant structure and transpiration rate. Leaf area and transpiration rates were also lower in this case, the discussion of which is dealt with in a later section.

ii) Stomatal conductance: The similarity of the effect of water stress on the rates of transpiration and photosynthesis (Brix 1962) and the closer relationship between oscillations of photosynthesis and transpiration (Troughton 1969) both point to a dominant control on transpiration. The effect of depletion and replenishment of soil water on transpiration, as regulated by the leaf stomates is of specific importance to water use and its efficiency in crop production.

From measurements of water relations of sorghum crop we found that irrigated sorghum crop exhibited higher stomatal conductance with values exceeding 0.5 cm/sec during most of the day, indication perhaps, of better photosynthetic activity than the unirrigated sorghum canopy which showed stomatal closure much earlier than the irrigated sorghum plants (Sivakumar et al. 1978). Diurnal variation in the stomatal conductance in the 0-30, 30-60, and 60-90 on canopy layers showed that in the unirrigated sorghum canopy, stomatal conductance in the 30- to 60-cm layer rarely exceeded 0.3 cm/sec whereas the leaves in the 60- to 90-cm layer consistently showed less than 0.1 cm/sec. Measurements made on a day following a 11 cm supplemental irrigation showed that stomatal response was similar in both irrigated and unirrigated sorghum. However, within the next four weeks, in the unirrigated sorghum, stomatal conductance was greatly reduced and no longer responded to increasing irradiance. Stomata continued to respond (although somewhat less strongly) to irradiance in the irrigated sorghum. A plot of the stomatal conductance against the leaf-water potential and 'limiting factor analysis' suggested that stomatal conductance at higher ranges of leaf-water potential was mainly dependent on radiation, whereas the same became increasingly dependent on leaf-water potential as levels of stress increased, explaining the lower use of incident radiation in unirrigated sorghum. Crop conductance, calculated from the stomatal conductance and leaf area index in different canopy layers, differed by a factor of two to five as stress increases (Seetharama et al. 1978).

In a study that involved application of two irrigations measuring 40 mm each either at early vegetative growth or anthesis or grain filling to a millet crop grown during the summer season at ICRISAT Center, we found that millet showed a significant adaptability to moisture stress. Stomatal closure during conditions of water stress and recovery with supplemental irrigations was evident in all treatments but more significant when moisture stress was released at the time of anthesis.

It is, however, recognized that as in the case of leaf-water potential, there cannot be a single unique relationship between stomatal conductance and soil water. As Jarvis (1976) described, 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. The implications of the influence of vapor pressure deficit are discussed in the section on transpiration.

iii) Leaf temperature: When the disparity between transpiration and absorption of water increase, leaf-water deficits develop. Subsequently stomata close, transpiration increases and leaf temperatures rise. We found from the pattern of the water use (mm/day) measured at different distances from the line source on three different dates during a one month period following the application of the line source that the water use decreased progressively. Mean daily leaf temperature of sorghum for the corresponding dates also showed a pattern that approximated very closely the changes in the water use pattern.

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 (LATD). Ehrler and van Bavel (1967) showed that this differential is strongly related to soil-water availability. The summation of LATD over time, according to Jackson et al. (1977), yielded a factor termed the 'Stress Degree Day' (SDD). We have measured the SDD for three sorghum genotypes grown with and without supplemental irrigations in a medium deep Alfisol during the post-rainy season. SDD for the three genotypes (CSH-8, CSH-6, and M-35-1) were -240, -241, and -352°C in the irrigated treatment and -184, -177, and -266°C in the unirrigated treatment. However, since the days to physiological maturity were different in the two treatments, for the three genotypes, it would be unrealistic to compare the moisture stress response of the genotypes based on the cumulative values. For the measurement period, the average LATD was -3.81, -4.73, and -4.63°C in the irrigated sorghum and -3.12, -3.93, and -3.64°C in the unirrigated treatment for the three genotypes. These data show that stress induced increase in leaf temperature averaged over the measurement period was the least in CSH-8 followed by M-35-1 and CSH-6.

Cumulative LATD measured for a period of 15 days in a millet crop was consistently lower in the treatment which received irrigation every 10 days. The contrast in LATD in the treatment which received supplemental irrigations during the period of measurement was quite evident.

When evaporative cooling cannot be maintained with reduced availability of soil water canopy temperatures rise above the air temperature. A plot of the 5-day averages of daily canopy LATD against the measured available soil water, pooled over the three moisture regimes in a chickpea crop showed the expected trend that the temperature differential in the chickpea canopy would tend to become positive with reduction in the available soil water (Fig. 2).

Similar measurements in the case of groundnut showed that the stage of growth at which the moisture stress is imposed on the crop must be considered in interpreting the cumulative LATD value in relation to the final yield measured. However, the seasonal trends in the cumulative LATD provide clues regarding the severity of moisture stress gradient imposed by the use of the line source irrigation.

iv) Transpiration: In the context of the crop water use, growth and development, transpiration has often been regarded as a necessary evil. Transpiration prevents excessively high temperatures. The cooling effects of high transpiration rates under low humidities and high temperatures were of considerable benefit to plant survival and growth. However, when transpiration exceeds water absorption, plants may reduce transpiration through a reduction in leaf area or through closure of stomata in which case the plant growth will be restricted.

From measurements of leaf and air temperature, leaf stomatal resistance and wind speed, we attempted to calculate the transpiration from the leaves of two sorghum genotypes grown with and without irrigation on a medium deep Alfisol. Calculated transpiration rates were higher for the sorghum hybrid CSH-8 in comparison to the variety M-35-1. During the second year of this study we could measure the actual transpiration rates in the field every day throughout the growing season by means of a steady state porometer. Cumulative transpiration rates computed from the daily transpiration values showed that again highest transpiration rates were recorded in the case of CSH-8 (Table 2). Average transpiration/day calculated from the cumulative totals also showed that stress induced adaptation ability was most evident in the case of the two sorghum hybrids followed by the variety M-35-1. Transpiration rates as µg of water/cm^2 of leaf area/sec were measured on the upper most leaf in each genotype. Since the maximum LAI recorded in the three genotypes was different, one useful way of interpreting the transpiration rate measured on the top leaf in terms of the canopy response is to compute weighted transpiration rates from the average transpiration rates by using the maximum LAI recorded for each genotype. The weighted transpiration rates show that only CSH-8 of the three genotypes tested was able to show adaptation to stress by cutting down transpiration while the other two genotypes in fact increased transpiration under limited water application.

As discussed earlier, the importance of atmospheric parameters such as vapor pressure deficit in modulating the relationship between moisture stress and transpiration and associated plant parameters like the stomatal conductance, cannot be ignored. In our study on the response of groundnut to moisture stress using a line source sprinkler irrigation, we have monitered the transpiration from the groundnut using a steady state porometer and the saturation deficit above the crop. Data collected from a treatment where the line source irrigation was given every 10 days throughout the growing season showed interesting trends. Close to the line source where a total of

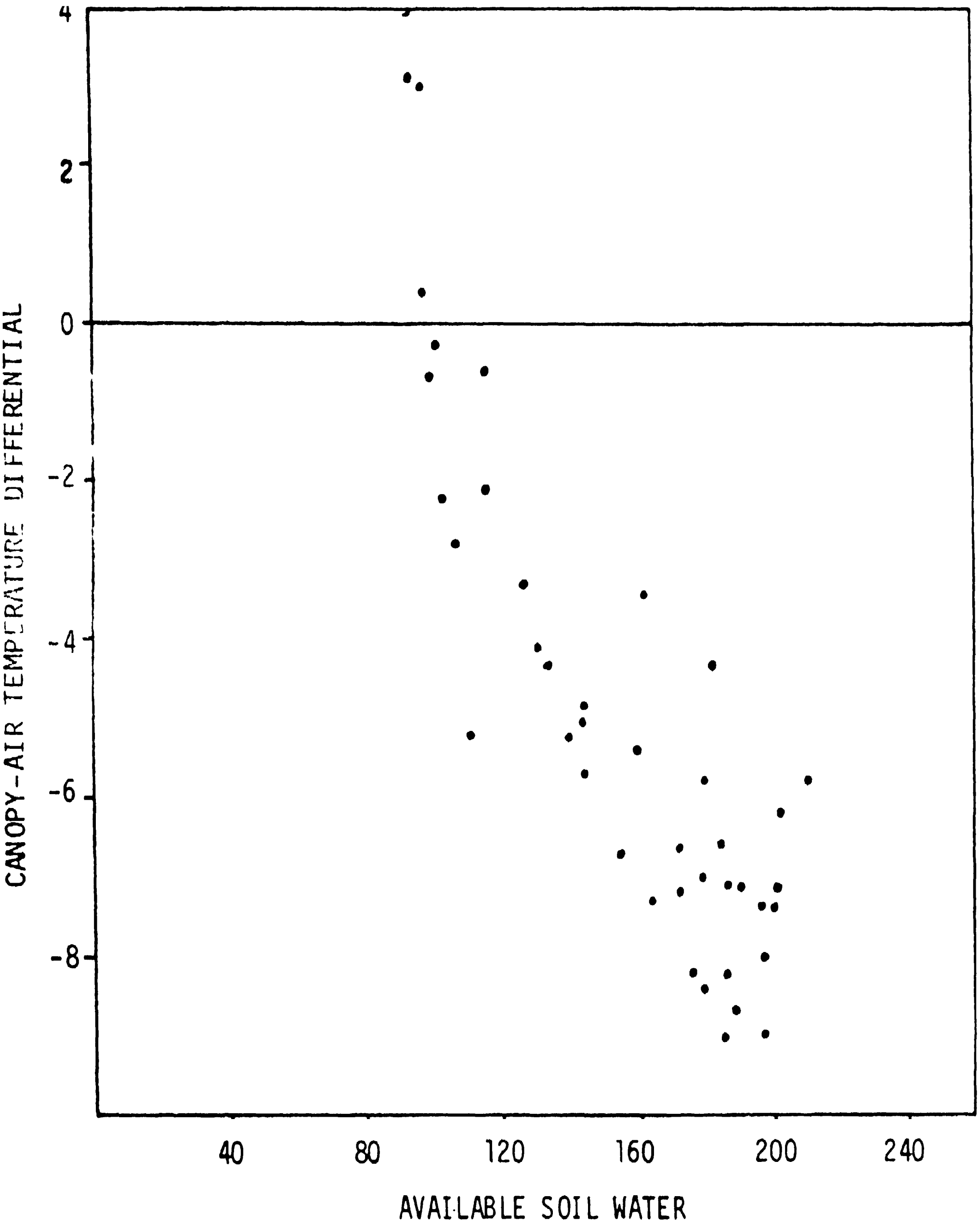

Figure 2. Relationship between leaf-air temperature differential and available soil water for chickpea (data pooled for different treatments).

Table 2. Transpiration rates of three sorghum genotypes grown on an Alfisol under two moisture regimes during the 1980-81 postrainy season at ICRISAT Center

Parameter	CSH-8		CSH-6		M-35-1	
	Trt. A*	Trt. B*	Trt. A	Trt. B	Trt. A	Trt. B
1. Measurement period (days)	63	59	51	45	76	76
2. Cumulative transpiration (μg/cm²/sec)	685	405	559	346	541	443
3. Transpiration/day (μg/cm²/sec)	10.9	6.9	10.9	7.7	7.1	6.7
4. Maximum LAI	2.96	2.58	1.82	1.08	2.86	2.02
5. Weighted transpiration/day (μg/cm²/sec)	3.68	2.67	5.99	7.13	2.48	3.02

*Trt.A: Four supplemental irrigations measuring 75, 78, 71, and 50 mm at 10, 28, 39, and 70 DAE.

Trt.B: Two supplemental irrigations measuring 60 and 85 mm at 10 and 39 DAE.

670 mm of water was given to the groundnut crop, measured transpiration rates showed no reduction even up to a saturation deficit of 10 mb (Fig. 3). At a distance of 9 m from the line source where the crop received only 335 mm of water with increase in saturation deficit up to 5 mb,transpiration also increased. Further increase in saturation deficit resulted in a decrease in the transpiration. Groundnut grown 18 m away from the line source experienced the most severe effects of water stress as is evident from the low transpiration rate. In this case also with increase in saturation deficit beyond 5mb, the transpiration showed a rapid decline.

From the total dry matter recorded at physiological maturity, final grain yield and cumulative transpiration measured for three sorghum genotypes grown with and without irrigation relationship of transpiration to total dry matter and grain yield was examined (Fig. 4). The data show that with decrease in cumulative transpiration from 685$\mu g/cm^2/sec$ to 346 $\mu g/cm^2/sec$, the decrease in dry matter and grain yield was linear.

c) Water Use-Crop Growth Relations

i) Leaf area: Since the growth and development of a plant depends in simplest terms, on the progressive initiation of tissue and organ primordia and on the differentiation and expansion of the component (Slatyer 1969), it follows that leaf initiation and expansion should be very sensitive to moisture stress. Over the growing season diminished leaf enlargement caused by short periods of water deficits could result in a substantial reduction in total leaf growth.

The effect of differential profile water depletion on sorghum response on a medium deep Alfisol was investigated in a two-year study and the results showed that the size and duration of crop canopy were markedly affected. The leaf area durations (LAI days) were 227, 122, 188, and 183 respectively in treatments where the crop was irrigated at 10-day intervals, not irrigated 35 days after sowing (DAS), not irrigated 35-65 DAS but irrigated at 10-day intervals later, and not irrigated from 65 DAS.

As plant development changes, the ratio of evapotranspiration to open pan evaporation (ET/Eo) also changes. The relationship between ET/Eo and LAI studied for a sorghum crop (Fig. 5) showed that when evapotranspiration in relation to open pan evaporation could be maintained consistently higher through extraction of soil water, the canopy leaf area also increased till the LAI reaches a maximum. Later, the decrease in LAI modulated the decrease in ET/Eo indicating that rate of water use was limited by the assimilating area. However, in the case where the sorghum crop was not irrigated 35 DAS, the evapotranspiration was limited by the soil water availability resulting in a rapid loss in leaf area.

ii) Dry matter: Net radiation which determines to a large extent the transpiration rate, and solar radiation, which determines photosynthesis are linearly related

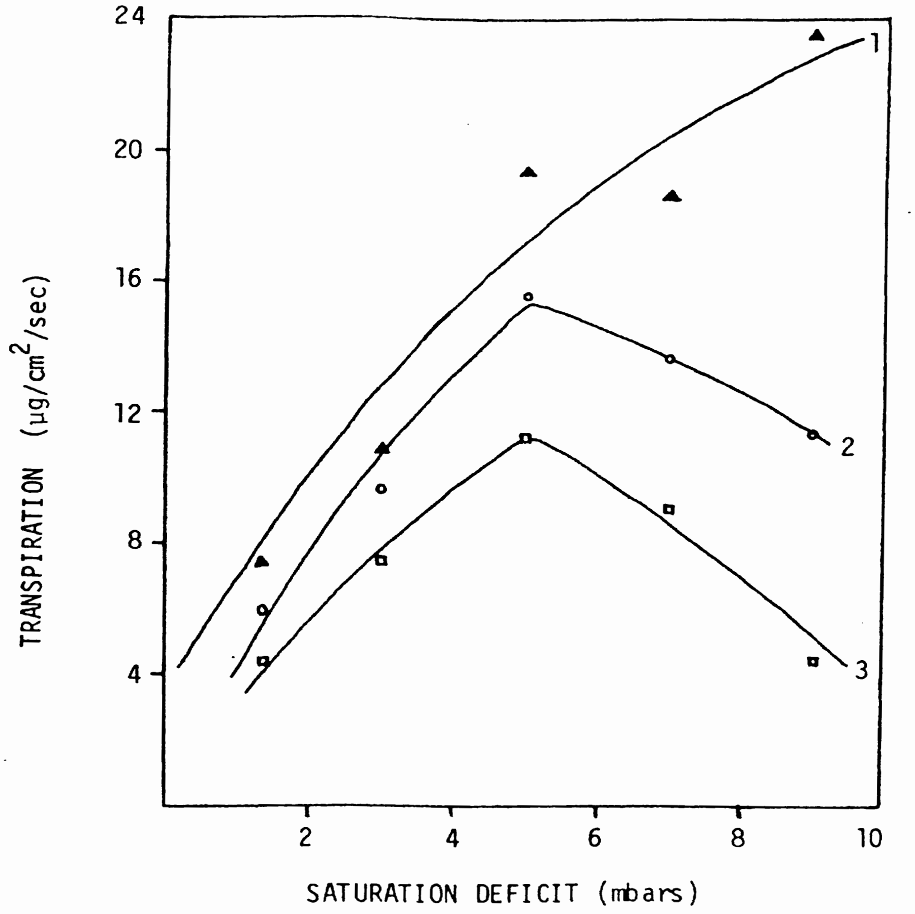

Figure 3. Transpiration from groundnut as related to the saturation deficit of air. The treatments refer to groundnut grown (1) close to the line source, (2) 9 m from the line source and (3) 18 m from the line source.

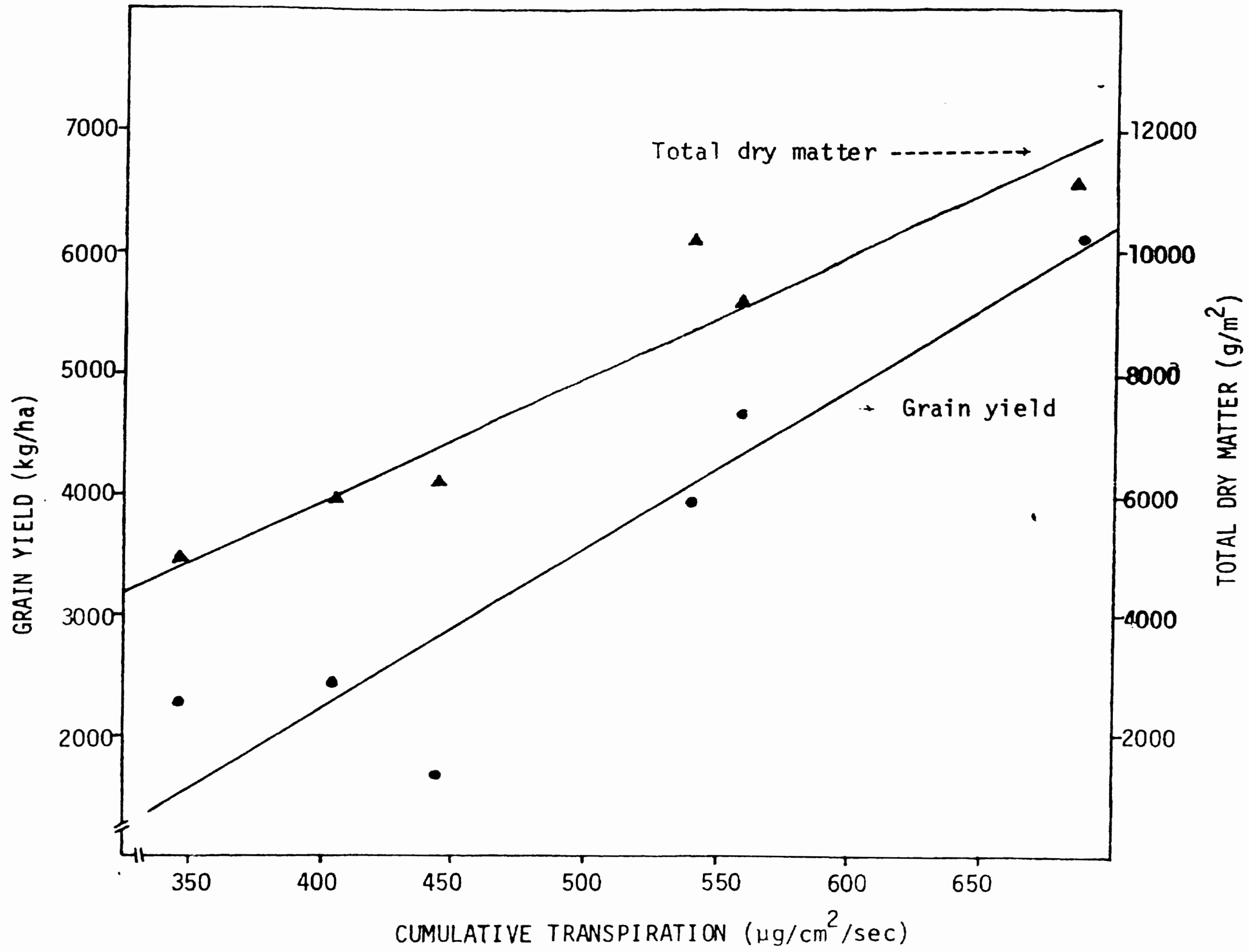

Figure 4. Relationship of total dry matter and grain yield of sorghum to cumulative transpiration (data pooled over 3 genotypes).

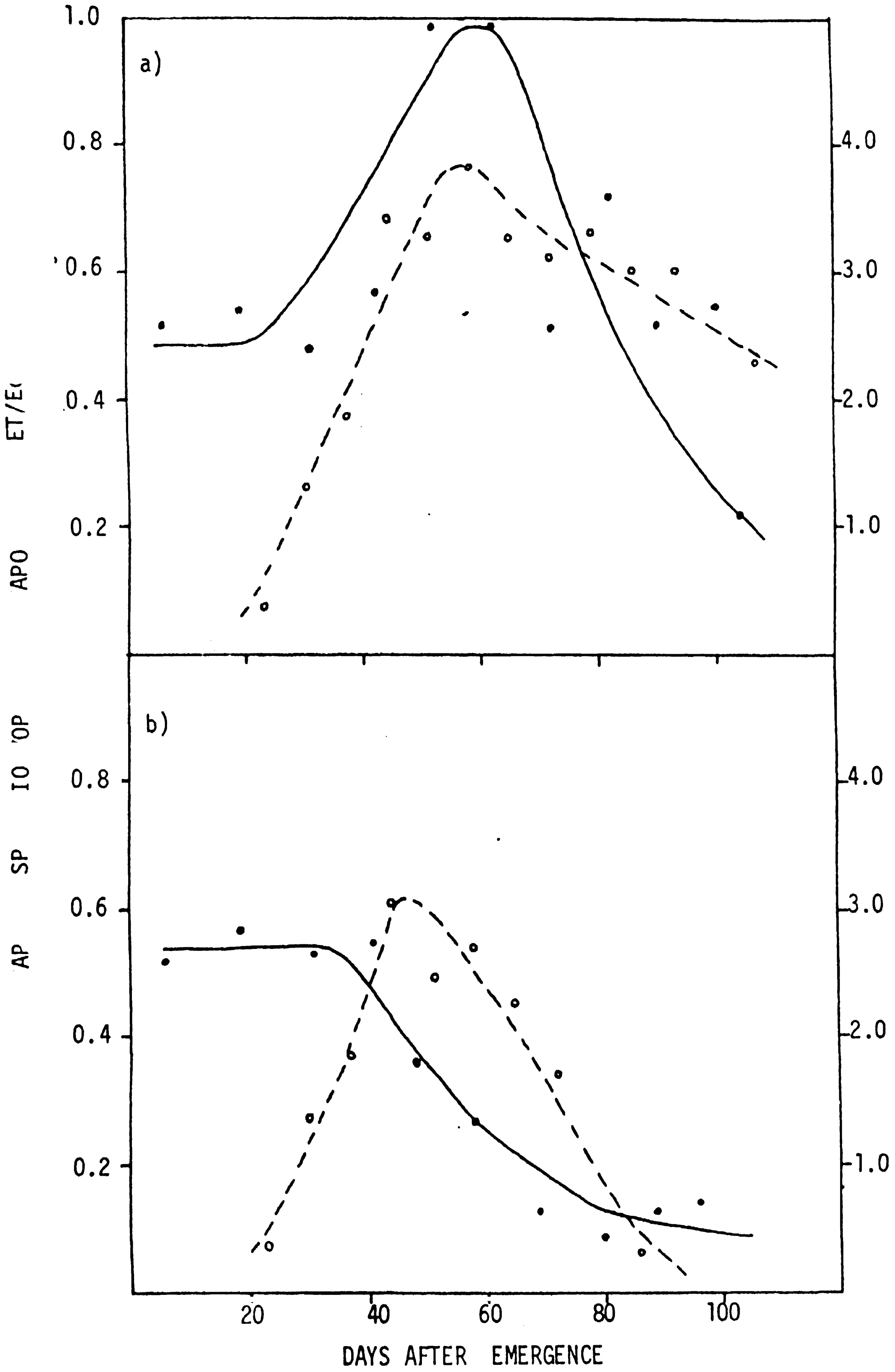

Figure 5. Water use as related to leaf area index of sorghum a) Irrigated 10 days intervals, and b) Unirrigated from 25 days after emergence to maturity

(Monteith 1965). Hence it could be surmised, as De wit (1958) did, that transpiration or water use and dry matter should be linearly related.

Our studies with sorghum showed that water use and dry matter are linearly related. The rates of dry matter accumulation and of water-use decreased as profile water depletion became more severe but the ratio between the two remained uniform (Fig. 6). It is interesting to note that cumulative transpiration rates measured in the field with a steady state porometer were also linearly related to the dry matter produced by sorghum (Fig. 4).

Total growth of millet crop was reduced by 30 percent if the stress was imposed from 48 DAE (days after emergence), while stress imposed from 30-64 DAE resulted in a 40 percent reduction in dry matter (Alagarswamy et al. 1977). Similar results were also obtained in an experiment evaluating the efficacy of application of two supplemental irrigations during the early vegetative growth, flowering or grain filling. Most severe effect of water stress on dry matter production was evidenced when stress was imposed from 20 to 58 DAE.

iii) Yield and yield components: Availability of adequate amounts of water to ensure that the transpirational demands are met will result in rapid leaf development and production of dry matter. For species such as grasses whose yield consists wholly of vegetative growth, water use could be linearly related to yield. For crops whose economic yield is a reproductive organ, water use-yield relationships cannot be so simply correlated because even when the dry matter and water use are linearly related, the partitioning of total assimilates into the heads and grain is a complicated subject (Brouwer 1962).

Grain yield of sorghum as related to its water use observed in an experiment involving a line source irrigation system is shown in Figure 7. The curvilinear relationship is not unexpected in the context of the earlier discussion on transpiration and dry matter. At the high water use rates, the production potential was fully expressed. Part of the reason for the observed relationship could be the nature of data set used which includes yields obtained with moisture stresses imposed at different growth stages. A similar trend was also observed for groundnut (Fig. 8) except that in this case yields have been plotted as a function of applied water instead of water use.

In terms of the yield components, it is commonly understood that moisture stress would reduce the size of the head as well as the seed number. In an unirrigated sorghum the grain number ($1000/m^2$) was 9.84 while the seed size (g/100 seeds) was 2.29. When 19 cm of water was applied to the crop, grain number improved to 16.45 and seed size increased to 2.98. The weight of the head of irrigated sorghum was twice that of the unirrigated crop.

In the case of a millet crop that was subjected to moisture stress from 30 to 64 DAE, it was observed that the seeds per panicle were 589 and the seed size (g/100 seeds) was 0.48 while in the control they were 865 and 0.64 respectively. Although

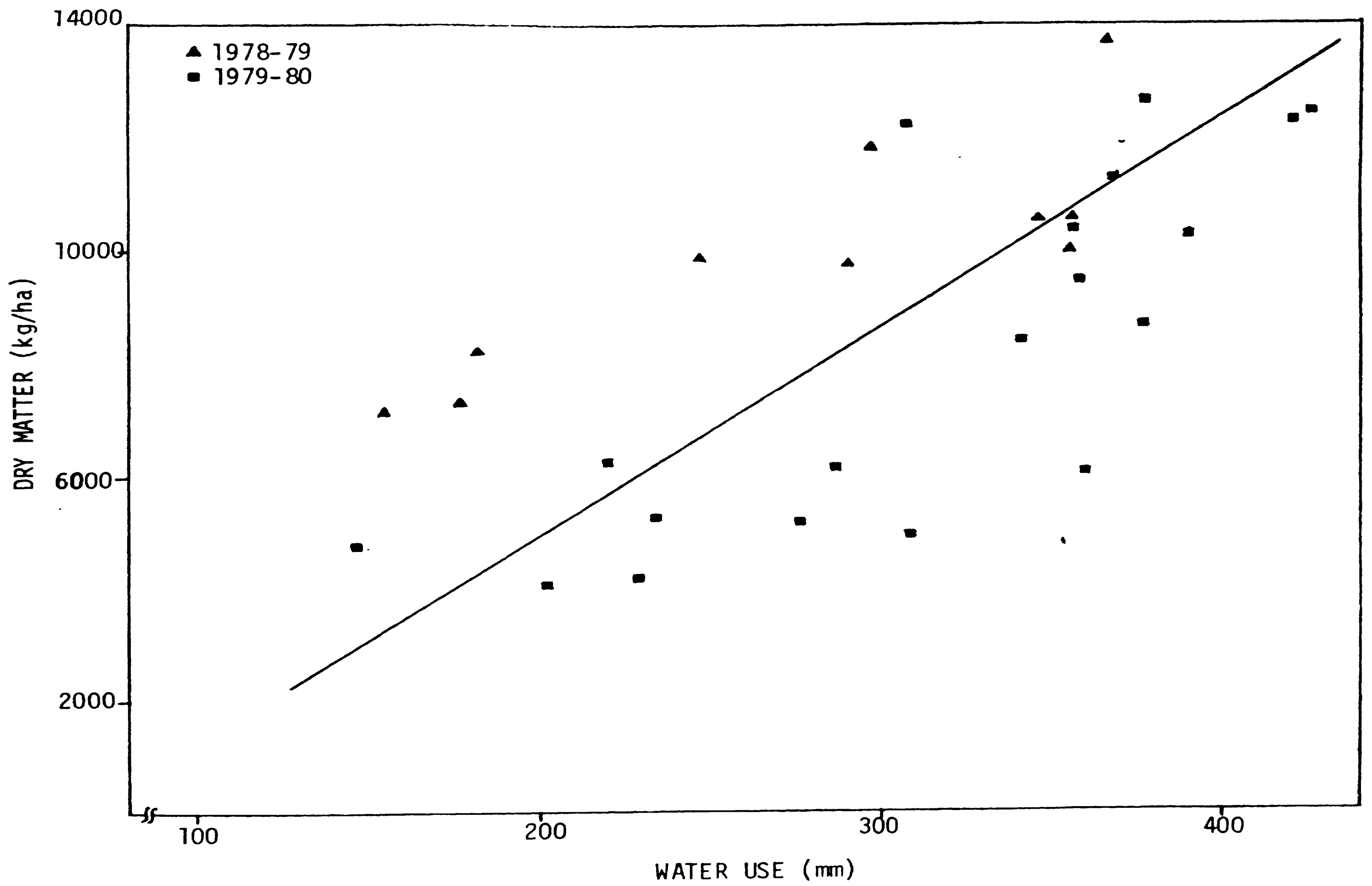

Figure 6. Dry matter production in sorghum as related to water use by the crop. Symbols refer to

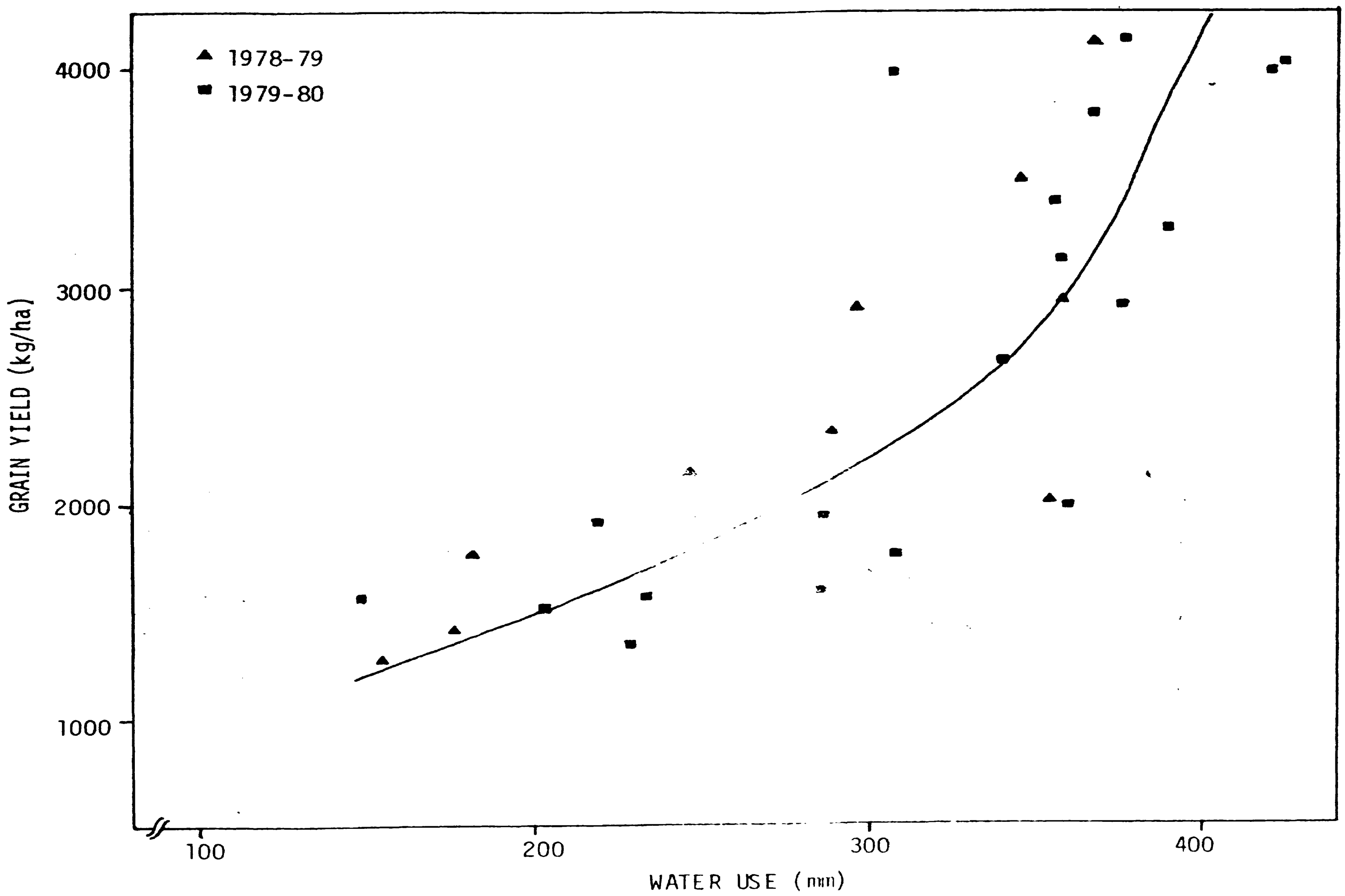

Figure 7. Grain yield in sorghum as related to water use by the crop. Symbols refer to data collected during two different seasons.

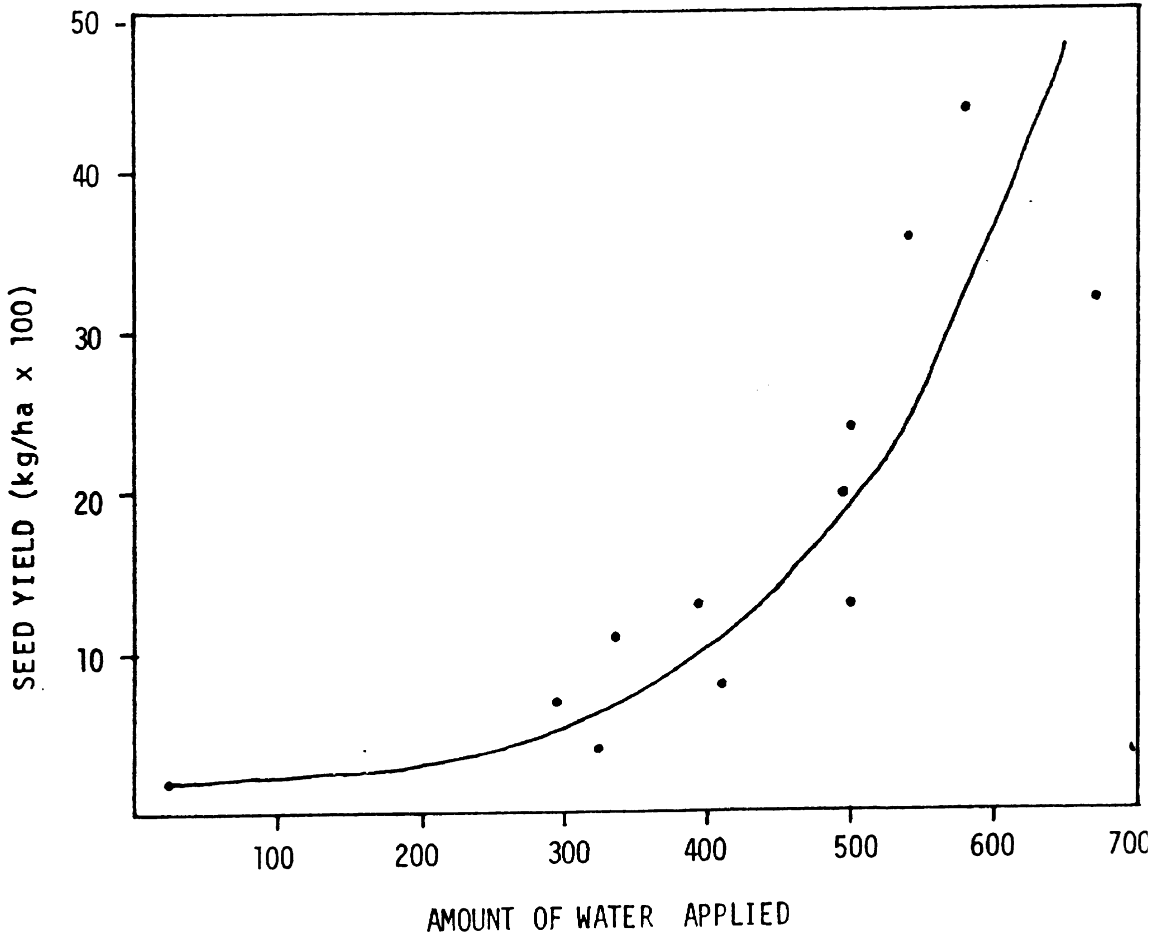

Figure 8. Response of groundnut to applied water.

the number of panicles was more or less similar (44 and 41 respectively), the reduction in the seed number and seed size led to decreased yield (1196 kg/ha) in the stress treatment as compared to the irrigated treatment (2115 kg/ha) (Alagarswamy et al. 1977).

In an experiment evaluating the response of chickpea to moisture stress, we found that yield reduction in the nonirrigated chickpea was mainly due to a reduction in the number of pods/plant. Seed weight (g/100 seeds) was also reduced, although not to the degree to which the pod number was reduced (Table 3).

iv) Importance of stage of crop growth: The growth of crop during its life cycle and the final yield produced is complex in nature, but moisture is necessary at all stages for maximum plant production. Moisture deficiency at a particular stage will affect the plant in a manner that may have a greater or lesser effect on final productivity. It is thus important to evaluate the effect of moisture stress at each stage of the growth and development.

In a study on the response of groundnut to moisture stress imposed at different phenological stages, we found that stress imposed from emergence to appearance of first pegs resulted in a slight reduction in vegetative growth during the duration of stress extending to 30 days. However, once the moisture stress was released and the crop received irrigations at 10-day intervals, the recovery from stress was remarkable and there was no reduction in the final kernel yield. However, when the stress was imposed after the crop was allowed to develop complete canopy and the kernel growth started i.e., after 85 DAE, there was a large demand for moisture, from the developing kernels and for transpiration from the canopy. Since the moisture supply was not adequate, the loss in leaf area was very severe and the final yield was significantly reduced (Table 4). In a study where supplemental irrigations were provided at different growth stages of millet, we found that millet could recover from stress imposed at early growth, if supplemental irrigations are provided before and around time flowering is completed. A prolonged spell of water stress during the stage of both early vegetative growth and flowering could reduce the yield of millet crop substantially.

The effect of moisture stress imposed at selected phenological stages of two sorghum genotypes was studied on a medium deep Alfisol during the 1981-82 postrainy-season. Withholding two irrigations at the time of anthesis and grain filling decreased yields by 50% of both the sorghum hybrid CSH-8 and the variety M-35-1 (Table 5). Moisture stress by withholding two irrigations at the time of panicle initiation did not reduce the yields significantly. However, stress initiated at the stage of panicle initiation and continued up to anthesis by withholding three irrigations reduced the yield considerably. One significant conclusion that emerged from this study was from the results obtained in the treatments where sorghum crop did not receive four irrigations and yet outyielded the crop where only two irrigations were not given at the time of anthesis and grain filling. The reason was that a single irrigation given at the time of anthesis helped the crop in the former case to recover to some extent from the affects of moisture stress imposed by withholding irrigations during, and a 20-day period following, panicle initiation.

Table 3. Final yield and yield components of a chickpea crop grown on a medium deep Vertisol under different moistures during the 1980-81 postrainy season at ICRISAT Center

water applied (mm)	Yield (Kg/ha)	Pod number per plant	Seed weight (g/100)
0	548	16	18.3
80	2020	37	21.4
160	2641	42	21.5

Table 4. Leaf area index (LAI) at maturity and yield of groundnut under moisture stress imposed at different stages

Treatment	LAI	Yield (Kg/ha)
1. Control	3.08	3152
2. Stress from emergence to appearance of first pegs	1.91	2373
3. Stress from flowering to last pod set	0	686
4. Stress from first kernel growth to maturity	0	384

Table 5. Yield response of two sorghum genotypes to moisture stress imposed at different phenological stages

Treatment	Grain yield (Kg/ha)	
	CSH-8	M-35-1
1. Control	5615	3780
2. Stress at panicle initiation	4510	3445
3. Stress at panicle initiation and anthesis	3200	1900
4. Stress at grain filling	2750	1930
5. Stress at panicle initiation and grain filling	3225	2403

In view of the results obtained in the studies discussed above, we have been paying more attention to specifying the stage of growth at which moisture stress is imposed and quantifying the affects due to this stress. Multilocation and time series experiments on moisture stress should take these into consideration in interpreting the results obtained.

d) Response Curves and Water Requirements

In the semi-arid tropics where the seasonal variability in rainfall is large which influences the profile moisture content and distribution in the dry season following the rainy season, the response to applied water at any time during the growing season could be variable. This could be illustrated from the responses obtained for a chickpea crop given two or four supplemental irrigations during two postrainy growing seasons i.e., 1978-79 and 1979-80 (Sardar Singh and N.P. Saxena, unpublished data). Response curves for chickpea (Fig. 9) show that during the 1978-79 growing season the response is linear while in the 1979-80 season the response was curvilinear. An analysis of the pre-season rainfall data shows (Table 6) that a linear response was obtained during the first growing season because the profile was relatively dry when chickpea was planted while in the second season the soil profile had more favorable moisture.

Even within a growing season, depending on the time of planting, the response to applied water could be variable. Data obtained by our pigeonpea physiologist (Y.S. Chauhan, unpublished data) show that a pigeonpea crop planted in September does not respond to supplemental irrigations beyond two irrigations. However, if the planting is delayed progressively to October and November, the response up to 3 supplemental irrigations is evident (Fig. 10).

Our cropping system scientists showed that under moisture stress intercropping systems show greater relative advantage. Yield response curves for sole crops of sorghum and groundnut and sorghum/groundnut intercrop to water applied through a line source sprinkler irrigation showed that with increasing stress, advantage of the intercrop was more. Under conditions of stress, intercropped groundnut yields exceeded sole crop yields because of possible beneficial shading effect from the associated cereal crop.

Water use and water use efficiency data for several crops/cropping systems evaluated at the ICRISAT Center by different research programs are shown in Table 7. The data show that sorghum grown on the deep Vertisols during the rainy season extracted more water than either a sorghum/pigeonpea intercrop or maize or maize/pigeonpea or pigeonpea. Highest water use efficiencies also were recorded in the case of sorghum grown during the rainy season or during the postrainy-season under irrigation. Maize was next best crop in the water use with a sole crop of maize extracting more water than the intercrop of maize/pigeonpea. Water use of the millet crop was less but the water use efficiencies of the millet crop were comparable to those of maize, confirming that millet is a crop to be preferred under low moisture availability conditions.

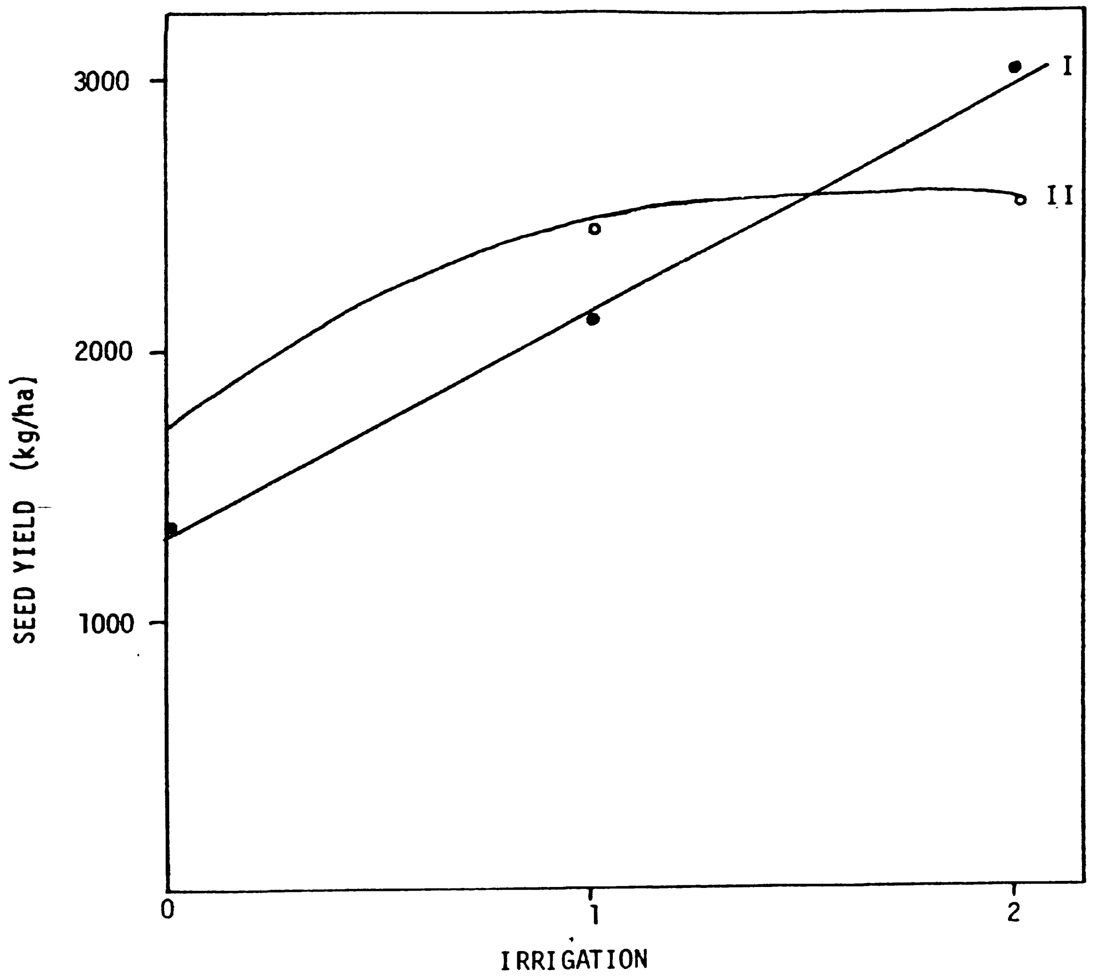

Figure 9. Response of chickpea to applied water during (I) 1978-79 and (II) 1979-80 growing seasons.

Table 6. Rainfall data during the rainy seasons of 1978 and 1979

Year	Rainfall (mm)					
	Jun	Jul	Aug	Sep	Oct	Total
1978	181	228	516	82	71	1078
1979	58	107	101	345	20	631

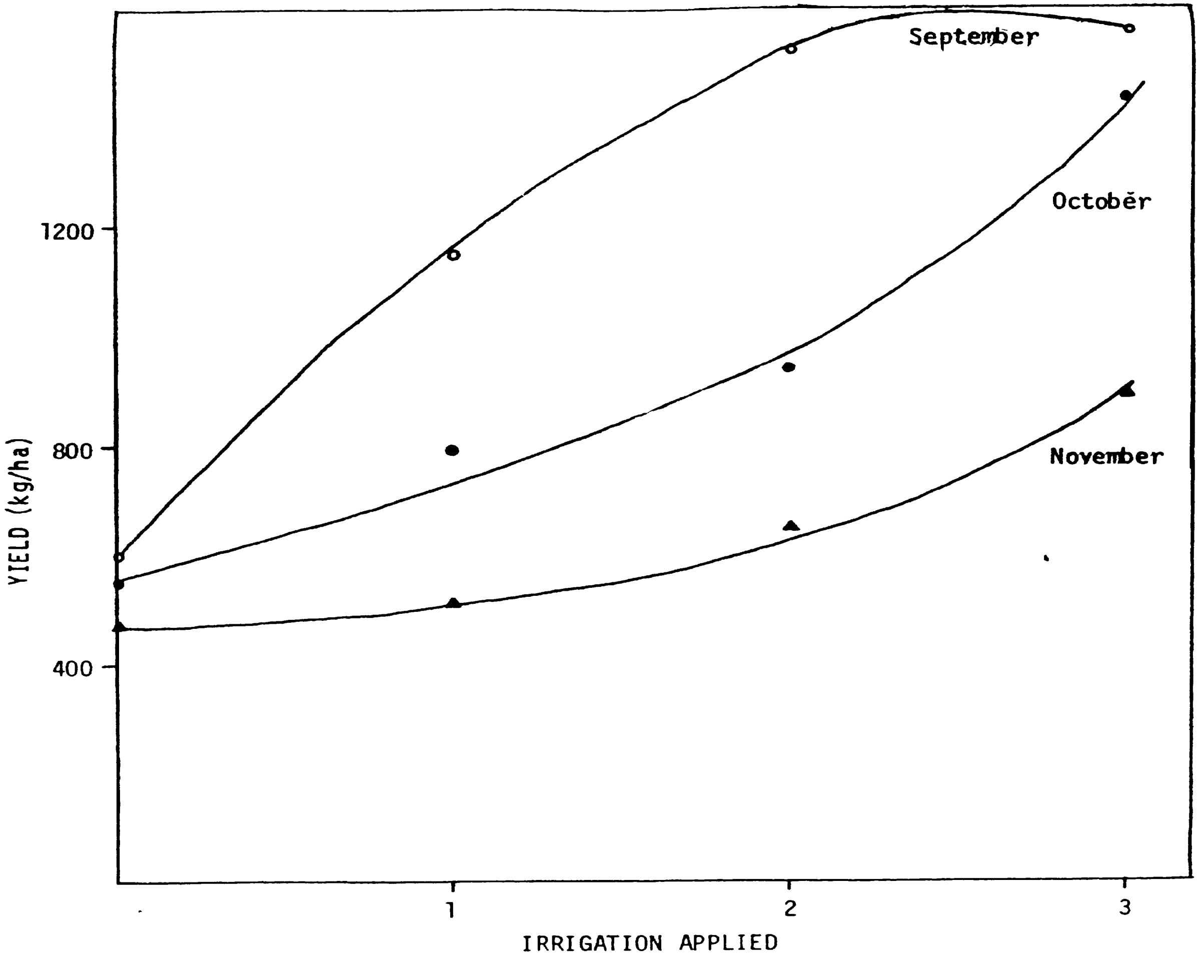

Figure 10. Response of pigeonpea planted at different times during the postrainy-season to applied irrigations.

Table 7. **Water use and water use efficiency for crops/cropping systems grown at ICRISAT Center, Patancheru.**

Crop/cropping system	Season	Soil	Water Use (Cm)	Yield (Kg/ha)	Water Use Efficiency (Kg/ha/cm)	Reference
1. Sorghum	Rainy	Alfisol	24.0	3700	154	Environmental Physics (1978)
2. Sorghum	Rainy	Vertisol	35.3	4467	127	Environmental Physics (1978)
3. Sorghum	Postrainy Rainfed	Vertisol	21.6	2430	113	Sivakumar et al. 197
4. Sorghum	Postrainy Irrigated (19 cm)	Vertisol	36.9	5990	162	Sivakumar et al. 197
5. Millet	Postrainy Rainfed	Alfisol	9.6	1110	116	Environmental Physics (1978)
6. Millet	Postrainy Irrigated(14 cm)	Alf.	15.5	1860	120	Environmental Physics (1978)
7. Millet	Rainy	Alfisol	15.9	2226	140	Reddy and Willey 197
8. Groundnut	Rainy	Alfisol	19.6	1185	60	Reddy and Willey 197
9. Millet/groundnut	Rainy	Alfisol	22.8	1227/840	91	Reddy and Willey 197
10. Pigeonpea	Rainy	Vertisol	33.5	--	--	Environmental Physics (1978)
11. Sorghum/pigeonpea	Rainy	Vertisol	33.3	4314 (Sorghum)	130	Environmental Physics (1978)
12. Maize	Rainy	Vertisol	23.1	3026	131	Sardar Singh and Russell (1980)
13. Maize/pigeonpea	Rainy	Vertisol	21.2	2480 (Maize)	117	Sardar Singh and Russell (1980)
Pigeonpea	Postrainy	Vertisol	19.6	1588	81	
14. Maize/pigeonpea	Rainy	Vertisol	24.6	2534 (Maize)	103	Sardar Singh and Russell (1980)
Pigeonpea	Postrainy	Vertisol	14.1	1072	76	
15. Chickpea	Postrainy Rainfed	Vertisol	16.2	1053	65	Environmental Physics (1978)
16. Chickpea	Postrainy Irrigated(6.7 cm)	Ver.	21.2	1145	54	Environmental Physics (1978)

Water use efficiencies of the pulse crops grown in pure stands were low. Chickpea and groundnut are fairly comparable although they were grown in different seasons. Computed water use efficiencies for pigeonpea refer only to the period after the maize crop was harvested in the maize/pigeonpea intercrop. Moisture use from one crop of sole pigeonpea monitered during the rainy season was high (335 mm) but water use efficiency in this case could not be computed as the water use data during the postrainy-season were not available.

It is significant to note that water use efficiency for a millet/groundnut intercrop was better than that of a groundnut crop grown in pure stands. During the postrainy-season water use efficiencies of irrigated sorghum were higher but not those for irrigated millet and chickpea.

LOOKING AHEAD

Maximization of crop production in the seasonally dry semi-arid tropics is limited by water stress and attainment of this goal is possible through improved understanding of the physical environment and all factors of crop response to moisture stress. Our studies over the past few years showed that there are many plant processes that are modified by water stress and that may contribute to loss of productivity. Antecedent seasonal weather, timing and intensity of stress during the season affect the crop growth and development and the magnitude of yield response observed. These relationships are complex in nature and cannot be viewed in isolation of related processes and factors that affect them.

We believe that the soil-plant-atmosphere continuum (SPAC) approach could help in relating the different factors involved in plant responses and in interpreting the final yields obtained. The physical processes operating in the SPAC should be understood with respect to rates and amounts of water transfer in the system. More specifically:

- The balance between the moisture supply and demand and its influence on the available water from the soil at different stages of crop growth will be monitered on a seasonal basis to examine the profile moisture dynamics.

- The rate of transpiration from the crop and plant factors that affect it such as leaf-water-potential, stomatal conductance and leaf temperature will be quantified with respect to associated environmental factors such as air temperature, vapor pressure deficit, wind speed etc.

- Seasonal variations in leaf area expansion, dry matter production and its distribution among different components as affected by different levels of moisture stress will be described and these data will be used to examine the differences in sensitivity to moisture stress at different phenological stages.

A stress index will be developed and tested for adoptation at the farm level under varying water supply conditions.

A minimum set of soil, crop, and climate data will be collected in all studies on crop moisture stress. These data will be used in developing and validating process-based, weather driven, soil, and crop simulation models.

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LAND AND WATER MANAGEMENT IN RAINFED FARMING SYSTEMS [1]

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SUMMARY

Land and water are the key elements of the resource-base of rainfed farming systems and strategies for effective management of these resources are intimately linked. This paper reviews ICRISAT's research approach for developing improved land and water management practices and their integration with other aspects of farming system. The small watershed-based farming systems approach which holds a good promise for management of Vertisols is discussed. The present status of research on Alfisol management, tank irrigation and runoff modeling at ICRISAT has been reviewed.

1. INTRODUCTION

The organization, activities and goals of Farming Systems Research Program at ICRISAT are based on the premise that a substantial improvement in the productivity of rainfed farming in the Semi-Arid Tropics (SAT) is feasible through a better management of resources -- natural as well as socioeconomic. The farming systems research begins and ends on the farm. It emphasizes problem oriented studies and is multi-disciplinary involving scientists, farmers, government and private industry (Swindale 1981). Land and water are the key elements of the resource-base of farming systems and their management strategies are intimately linked. At ICRISAT, several land and water management practices have been studied over the past few years. In these studies the interactive role of factors like climate, energy, crops, fertility, farm implements and socioeconomics vis-a-vis land and water management practices has been consciously recognized. The aim of this paper is to present the approaches and summarize some of the main research results relating to the following aspects:

- Land management practices for Vertisols and Alfisols, and watershed management.
- Water harvesting and recycling for supplemental irrigation.
- Runoff modeling.

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2. SOIL AND CLIMATE AT ICRISAT CENTER

Vertisols (black soils) and Alfisols (red soils) which are two of the most abundant soils in the SAT are found at the ICRISAT Center. Although they may occur in close association, their management requirements and runoff characteristics are very different. The most striking example is the fact that farmers crop Alfisols during the rainy season and most of the Vertisols only during the postrainy-season. During the rainy season, runoff is observed to occur earlier on Alfisols than on Vertisols. Their contrasting nature is attributed primarily to differences in types and amount of clay, moisture holding capacity, workability and other associated characteristics. Vertisols are dark calcareous soils with depths greater than 90 cm. Due to the high content of the montmorillonitic type of clay shrinkage during drying is pronounced as is swelling during wetting. When fully recharged, Vertisols contain from 200-300 mm of available moisture sufficient enough to grow a postrainy-season crop (Virmani 1980). Because of the clay type and the relatively high clay content (50 to 60%), these soils are usually imperfectly drained and have a moderate low hydraulic conductivity. Alfisols are relatively better drained with a moderate hydraulic conductivity. They have variable soil texture ranging from loamy sand to sandy loam at the surface and gravelly clay in the subsurface. They contain 5-15% clay with the clay content, dominantly kaolinite, generally higher in the subsurface layer.

Because of the differences in their clay mineralogy, Vertisols tend to shrink and form cracks when dry while Alfisols tend to form surface crust in drying after heavy rains. Their infiltration is greatly influenced by this difference in behavior as shown in Table 1 (Krantz et al. 1978).

Thus, inspite of the low infiltration rates of Vertisols, the water intake rate early in the monsoon is high due to the deep cracks and high water holding capacity. The cracks continue to exist as such until sufficient wetting occurs and then the infiltration decreases sharply. In contrast, the initially high infiltration rate of Alfisols drops down quickly and is often greatly reduced during the early rainy season by surface sealing caused by the impact of rain drops on the bare soil.

From an agricultural standpoint the Hyderabad area and much of the SAT can be divided into 3 seasons (Krantz et al. 1978).

- Humid or rainy season of 100-110 day duration. This season, in which rainfall exceeds evapotranspiration, is characterized by a number of high intensity storms and occasional prolonged rainless periods. The rainfall ranges from 600-1000 mm/yr with about 85 percent occurring during the rainy season. With improved soil, water and crop management, this period has a high potential for crop production.

- Cool, dry postrainy season of 140-150 days. In this period there is little or no rain, and crop production is dependent mainly upon stored soil moisture and, where feasible, on stored water from tanks or shallow wells. Crop production during this season is better adapted to the deep Vertisols because of their high moisture-retention capacity. However, where water has been stored, crops can be grown on Alfisols and shallow Vertisols by use of supplemental irrigation.

Table 1. Initial and equilibrium infiltration rates of Vertisols and Alfisols at the ICRISAT Center (based on field measurements using double concentric basins)

Time from start (hrs)	Infiltration rates Vertisols (mm/hr)	Alfisols (mm/hr)
0 - 0.5	76	73
0.5 - 1.0	34	18
1.0 - 2.0	4	15
After 144	0.21 + 0.1	7.7 + 3.7

- Hot, dry season of 100-120 day duration. In rainfed agriculture this this season is not well suited for crop production because of the high water requirement. This period is however, well suited for land development for improved resources utilization, for land preparation, and for crop sanitation involving weed -- and insect -- source reduction. Although the total rainfall during this period is very low, it is characterized by occurrence of one to three high-intensity storms which facilitates land development and preparation.

3. RESEARCH APPROACH

The land and water management research at ICRISAT is largely based on the analysis of problems on 'real world' farms and certain conventional ameliorative approaches like rainy season fallowing and contour bunding (Kampen and associates 1974).

Most of the component research is executed in small field plots under carefully controlled and manageable conditions. Although these experiments may not give complete answers to questions of actual implementation on a farm scale or to the economic issues involved, they are considered valuable for finding 'leads' for further studies. In order to provide a fuller expression to factors like runoff, erosion and drainage, field size plots of over 0.3 ha size have been used for evaluating some alternative land treatments like broadbed and furrow and graded flat. Natural watersheds of over 2 ha size have been used for simulating and studying practices like contour and field bunding, safe runoff and disposal and runoff recycling.

On-station operational research is considered as a necessary phase both to test the operational feasibility of practices and implements as a prior step to on-farm research and also to obtain accurate data on time dependent variabilities. This phase of research has been executed on natural watersheds to enable integration of land and water management practices with other technology components and to have simultaneous hydrologic, agronomic and economic evaluations of alternative farming systems. According to Kampen (1979), watershed is the natural framework for resource development in rainfed agriculture.

The on-farm research is conducted to test and adapt improved technology with participation of farmers, make adoption studies and provide data with demonstration value. Village watersheds of 10-30 ha size are being used for this phase of research.

4. SMALL WATERSHED APPROACH FOR VERTISOLS MANAGEMENT

The low productivity and soil erosion problems of traditional farming systems of Vertisols which are generally fallowed during the rainy season merited priority research attention. It was hypothesized that most of the Vertisols fallowed during the rainy season in Hyderabad region can be double cropped through an appropriate soil-, water-, and crop-management technology. In a computerized water-balance model involving 70 years of rainfall data, soil moisture retention capacity and crop requirements at Hyderabad, the median length of growing season in Vertisols was calculated as 26 weeks (Virmani 1980). In the traditional system of rainy season fallow-postrainy season cropping, the growing season is only 14 weeks. It was found that the practice of contour bunding on these soils leads to yield reduction due to waterlogging near the bunds (ICRISAT Annual Report 1975-76). Similar results were obtained at Bellary Center of the All India Coordinated Research Project on Dryland Agriculture (Chittaranjan and Patnaik 1977).

Evidently, a prospective technology for Vertisol management should include the following features (Virmani et al. 1981).

- Land and water management practices that reduce runoff and erosion, and that give improved surface drainage and better aeration and workability of the soil.
- Cropping system and crop management practices that establish a crop at the very beginning of the rainy season, that make efficient use of moisture throughout both the rainy and postrainy seasons, and that give high sustained level of yields.
- Implements for cultivation, seeding and fertilizing that enable the required land and crop management practices to be effectively carried out. The implements should be suited to animal and human sources of power.

a) Evaluation of Integrated Technology

Through the experimental studies at ICRISAT, a small watershed integrated approach for Vertisol management was evolved which includes the above mentioned features. The key components of this approach are:

- cultivating the land immediately after the previous postrainy-season crop when the soil is not too dry for working;
- improved drainage through provision of grassed waterways and use of graded broadbeds and furrow;
- dry seeding of rainy season crops before the monsoon rains arrive;
- planting of postrainy-season crops in the stubbles of rainy season crops after a shallow cultivation;
- the use of improved seeds and moderate amounts of fertilizers;
- improved placement of seed and fertilizers;
- timely interculture and weed control; and
- some attention to plant protection.

On-station operational research extending over 5 years (1976-77 to 1980-81) has shown that this improved watershed management approach including maize intercropped with pigeonpea can increase profits by about 600% compared with a traditional system based on a rainy season fallow followed by postrainy season sorghum or chickpea. This represents a rate of return on the added operating expenditures of 250% (Ryan and Sarin 1981). In addition to improvement in productivity, this approach has substantial resource conservation benefits as shown in Table 2. It is evident that runoff is reduced by about 50% and soil loss by over 80%.

It was found that absolute variability in profit is increased, although percentage variability is decreased. The needs for human labor increase by 250% or more and the pattern of labor use is changed. More labor is needed in the early months of the cropping year, even in April and May, when traditional farm labor use is minimal. Labor peaks occur at normal times but are much greater. If threshing and harvesting must be done by hand, the labor peaks are extreme, particularly in October and November when the first -- that is, the additional crop must be harvested and the second crop planted. There is also a greater need for the use of bullocks. Availability of bullock power represents a serious constraint for the smallest farmers, few of whom own bullocks (Ryan and Sarin 1981).

Institutional help is required to: help the smallest farmers obtain access to bullock power; provide for some community drains; and obtain credit for enterpreneurs to purchase the wheeled tool carriers. New marketing strategies may be necessary to cope with increased local supplies of crops. Storage facilities on the farm or in the village may be needed to prevent spoilage and to ensure that whatever is supplied to the market is in reasonable balance with demand (Swindale 1981).

All Vertisol regions of world will not be suitable for this type of technology. The ICRISAT agroclimatologists have delineated geographical locations of Vertisol regions in India where this technology is likely to hold promise.

For on-farm verification last year we chose a 15 ha watershed in a village called Tadanpally, 40 km north of ICRISAT. Although during 1981 the rainfall was 70% above normal, the watershed management approach has performed well. Two reasonably good crops were raised in the watershed area during 1981-82 where only one grew before. The economics of this improved system has been found to be extremely attractive with a rate of return on added expenditures of 244% (Ryan et al. 1982); the adoption and diffusion will be monitored over the coming years.

Similar on-farm verification studies are being initiated this year at Raisen district in the state of Madhya Pradesh and at Gulbarga district in Karnataka (both in India).

Table 2. Runoff and soil loss under two differently treated Vertisol watersheds at ICRISAT Center

Year	Rainfall (mm) (seasonal)	Broadbed and furrow layout with improved crop management system		Traditional flat with bunds, rainy season fallow system	
		Runoff (mm)	Soil loss tonnes/ha	Runoff (mm)	Soil loss tonnes/ha
1976-77	688	73	0.80	238	9.20
1977-78	586	1.4	0.04	52.7	1.68
1978-79	1125	273	3.40	410	9.70
1979-80	690	73	0.70	202	9.47
1980-81	730	116	0.90	166	4.58
Mean	763.8	107.3	1.17	213.8	6.93

(Source: Miranda, et al. 1982)

b) Evaluation of Land-Treatment Component

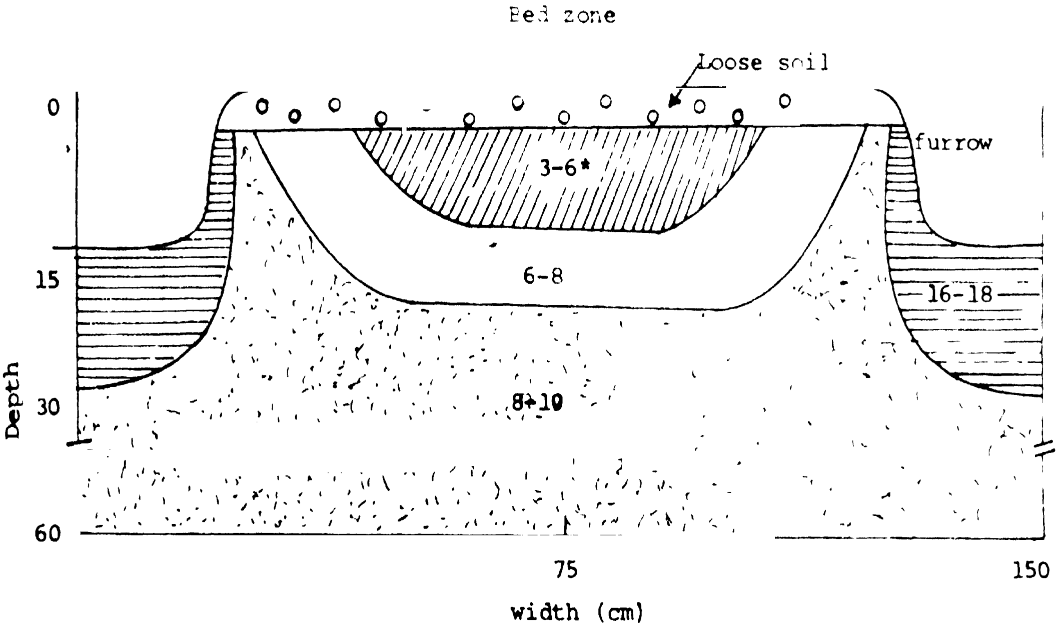
In the on-station operational research and on-farm studies described earlier, the multicomponent improved technology has been compared with traditional technology. A separate experiment was felt necessary to study the effect of land treatment component alone. This study (1976-77 to 1980-81) was conducted in field size plots with about 1.5% land slope to compare the 150 cm wide graded broadbed and furrow (BBF) with the graded flat cultivation keeping both the land treatments under improved level of inputs. Both the land treatments were laid on a grade of 0.4 to 0.8%. The BBF land treatment consists of two distinct zones: about 100 cm wide bed zone which is used for cropping, and about 50 cm wide furrow zone which is used for traffic. A sequential cropping of maize followed by chickpea was grown. It was noted that the BBF treatment has substantially lower penetration resistance in its cropping zone as compared to a corresponding zone in flat (Fig. 1). It was also found that during the wet spells airfilled porosity (measured using the difference method; Vomocil 1965) was substantially higher in 0-15 cm layer of cropping zone of BBF as compared to that in flat (Fig. 2). The runoff and soil loss were found to be slightly lower in the BBF as compared to the flat (Table 3). The average produce value was higher by about Rs 600/ha on BBF plots as compared to the flat. The BBF was observed to be particularly advantageous in years of high rainfall. The measurements by Ali Khani (1980) showed that draft is substantially lower in BBF system as compared to the flat. The lower penetration resistance on beds facilitated land preparation during the dry season and the placement of fertilizer and seeds in dry soil at about the desired 8-10 cm depth.

A detailed observation of time requirement for primary tillage, planting, and intercultivation operations showed that the semi-permanent BBF treatment results in considerable saving of time over graded flat as shown in Table 4 (Bansal and Srivastava 1981). Differences in time requirements may be due to several reasons:

- In the BBF treatment only the bed zone is actually tilled during the land preparation phase.
- Operations are speeded up because furrows guide animals and the wheeled tool carrier.
- There is less compaction in the bed zone.
- In the graded-flat treatment 2-3 harrowing operations were executed using the traditional blade harrow.

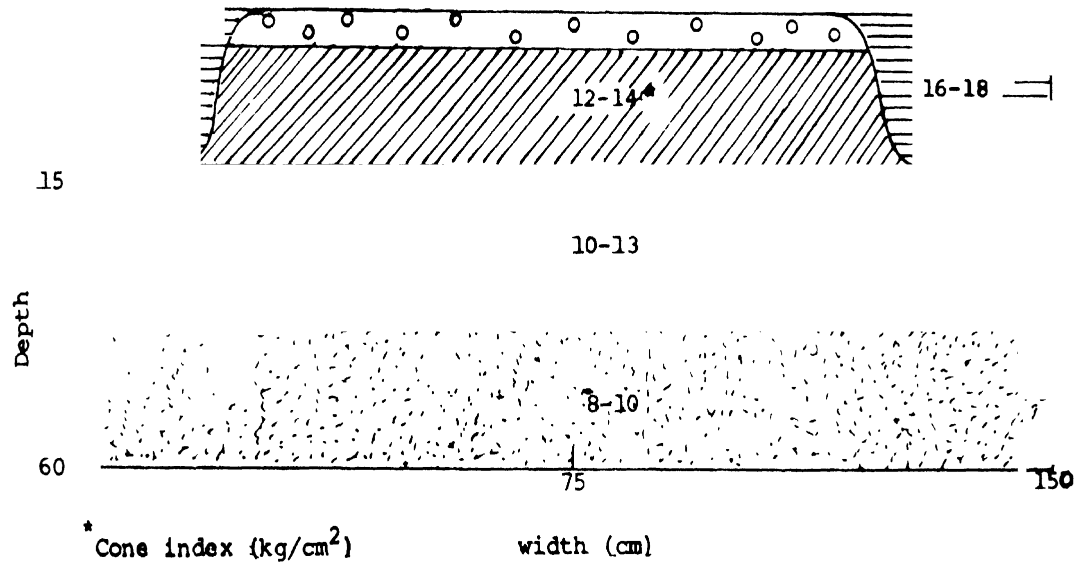
c) Layout of BBF

The layout of the BBF is flexible and has to be specifically designed for a given location keeping in view the watershed characteristics. A detailed topographic survey of the proposed watershed is first made and main and auxillary waterways are planned along topographic depression lines. The beds and furrows are laid at a grade of



Soil moisture (w/w basis)

Depth	Moisture content %
0-15 cm	24 ± 1.9
15-30 cm	31 ± 2.4
30-60 cm	33 ± 2.9



*Cone index (kg/cm^2)

Figure 1 **Penetration resistance zones under BBF and flat sys of cultivation on Vertisols at ICRISAT Center, 1980/81**

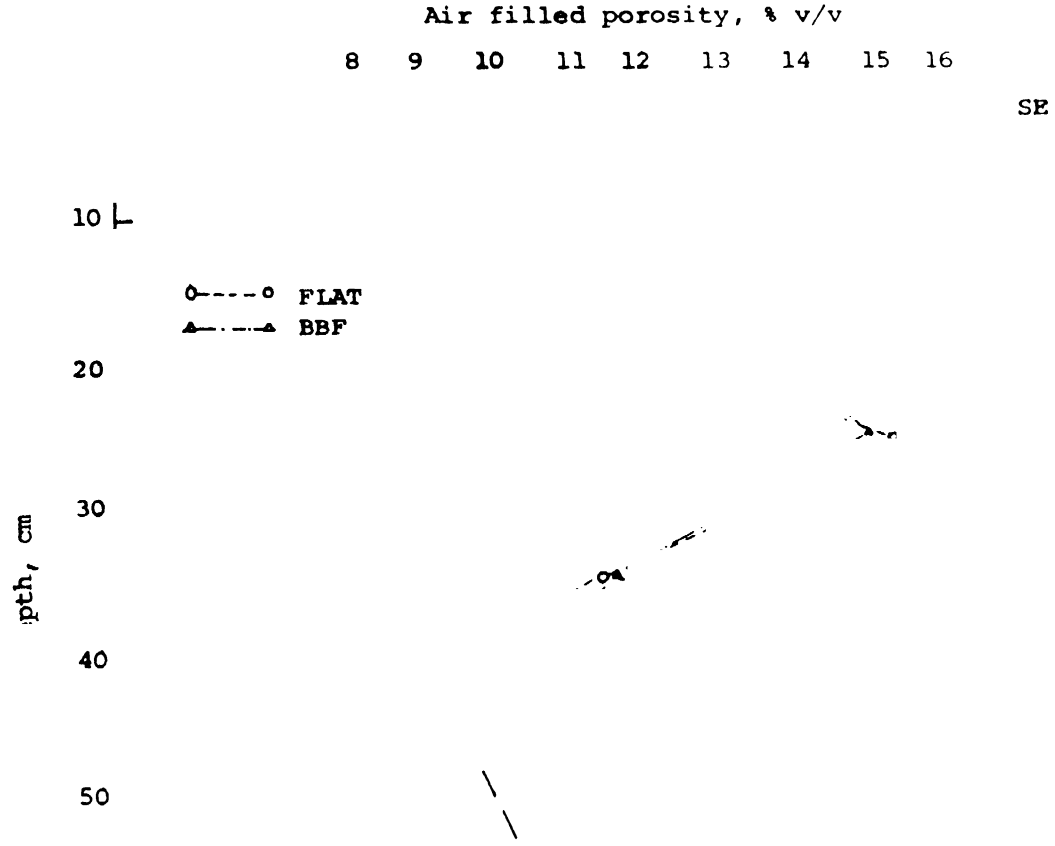


FIG. 2 : Air filled porosity during high moisture period

Table 3. Runoff and soil loss under broadbed and furrow (BBF) and graded flat cultivation in field-size plots in Vertisols with double cropping and improved level of crop management

Year	Rainfall, mm (seasonal)	Broadbed and furrow		Graded flat	
		Runoff, mm	Soil loss tonnes/ha	Runoff, mm	Soil loss tonnes/ha
1976-77	688	109.9	1.70	141.1	2.40
1977-78	586	0.6	0.04	0.8	0.04
1978-79					
(a) Seasonal	1125	250.6	1.38	240.8	2.10
(b) Excluding very heavy storms of 14-15 Aug.	907	97.0	0.86	132.1	1.81
1979-80	690	53.9	0.74	63.4	0.84
1980-81	730	61.7	0.48	77.1	0.49
Mean					
(a) Seasonal	764	95.3	0.89	104.6	1.17
(b) Excluding very heavy storms of 14-15 Aug. 1978	720	64.6	0.76	82.9	1.12

Table 4. Time required for various operations in BBF and graded flat cultivations in field size plots in Vertisols

Broadbed and furrow cultivation (BBF)			Flat cultivation		
Operation	Man-hour (per ha)	Bullock pair-hour (per ha)	Operation	Man-hour (per ha)	Bullock pair-hour (per ha)
Summer and rainy seasons			Summer and rainy seasons		
Moldboard plowing	5	2.5	Cultivation	12.6	6.3
Ridging	5	2.5	Cultivation	12.6	6.3
Cultivation	7.4	4.4	Harrowing*	7.0	7.0
Bed shaping	6.7	3.3	Harrowing	11.3	11.3
Planting and fertilizer application	9.0	3.0	Planting and fertilizer application	12.5	4.2
1st inter-row cultivation	12.0	4.0	1st inter-row cultivation	12.3	5.0
2nd inter-row cultivation	8.6	4.3	2nd inter-row cultivation	10.8	5.4
Postrainy season			Postrainy season		
Cultivation	6.3	3.1	Cultivation	8.4	4.2
Planting	18.0	6.0	Planting	15.0	5.0
Inter-row cultivation	7.6	3.8	Inter-row cultivation	10.6	5.3
Total	85.6	36.9		113.1	60.0

*Harrowing was done by using a traditional blade harrow. All other operations were done with the wheeled tool carrier and attachments.

0.4-0.8% and a maximum length of run of 100 m is used. The direction of beds is adjusted in a way to minimize top soil movement. The broadbed and furrow layout can be optimized in a natural watershed keeping the waterway length to the minimum essential, but it can also be laid out within a farmer's existing field boundaries where opportunity for adequate drainage is available. This is achieved by planning within the field boundaries and linking the field drains to main waterways of the watersheds. Three alternative landand water management approaches for a Vertisol watershed are illustrated in Figure 3. Approach (a) depicts contour bunding practice which often leads to water stagnation near bunds and reduction in crop yields. Approach (b) shows broadbed and furrow layout within the field boundaries, and field drains linked to main waterway of the watershed. In Approach (c) the broadbed and furrow layout has been planned after removing farmers' field boundaries. In the on-farm verification studies discussed earlier, the field boundaries have been respected and Approach (b) has been used for laying out broadbed and furrows.

5. LAND MANAGEMENT FOR ALFISOLS

The Alfisols are often characterized by relatively shallow depth, low water retention capacity and unstable soil structure leading to surface sealing during high intensity rain storms. The studies at ICRISAT have shown that considerable runoff occurs in these soils during the early phase of monsoon even when the profile is not yet adequately recharged.

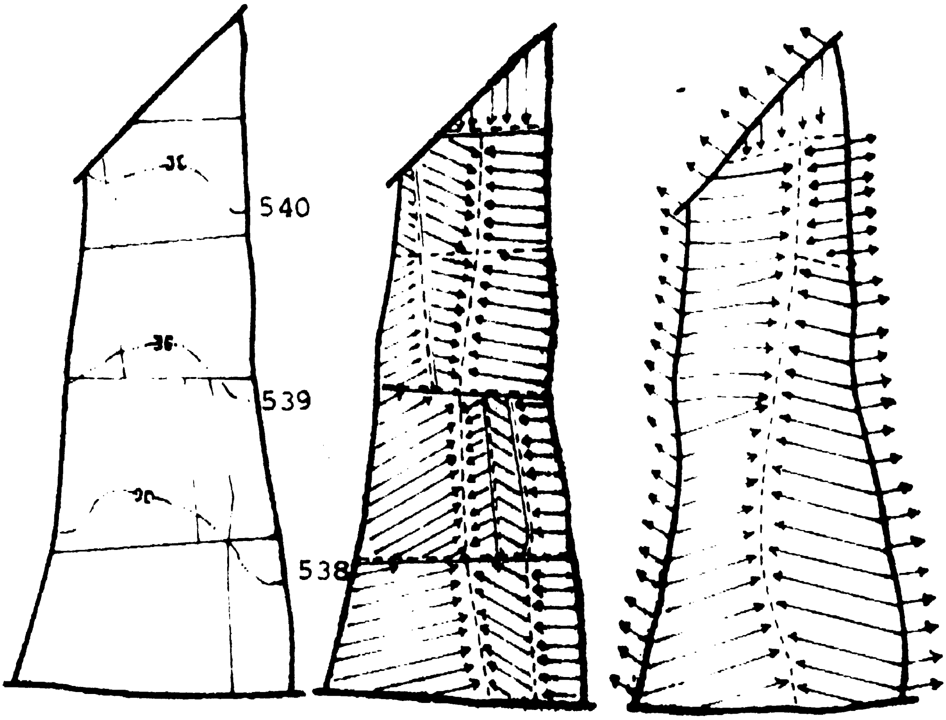
Contour and graded bunding are the locally recommended soil and water management practices for these soils. The major shortcomings with these practices are concentrated water flow along unprotected depression lines and uncontrolled soil and water movement along the main slope in the inter-terrace area. Cooperative studies have been conducted at ICRISAT and several research stations of the All India Coordinated Research Project on Dryland Agriculture to improve inter-terrace land management. It was hypothesized that if water flow is controlled through closely spaced furrows, this could improve in situ soil and water conservation. The surface configurations namely narrow ridge and furrow (75 cm), broadbed and furrow (150 cm), and a wave or sinusoidal shape (150 cm) were used as examples of this approach. These surface congigurations have not shown any appreciable and consistent improvement in crop growth environment over graded flat cultivation.

Based on the existing research evidence and experience, the practices of land smoothing, guide bunds and graded flat cultivation have been predicted to be suitable for Alfisol management in the Hyderabad region (Binswanger et al. 1980).

6. WATER HARVESTING AND SUPPLEMENTAL IRRIGATION

a) Runoff Storage

In designing the storage tanks for runoff collection at ICRISAT Center high storage efficiency was aimed at. The main factors considered were: area occupied by the tank in relation to the catchment area, seepage and evaporation losses, depth of the



a. Contour bunds

b. Broadbed-and-furrow layout within field boundaries.

c. Broadbed-and-furrow layout after removing field boundaries.

Bed and furrow direction
Field bunds
Grassed waterways
Contour bunds
][Waste weir

Figure 3: Three alternative land and water management approaches for a Vertisol watershed.

tank, and cost of construction. Some circular designs were tried to reduce the wetted surface in relation to the volume of water stored. Tanks of depths exceeding 2 m were preferred with a view to reduce the area occupied by the tank and to minimize evaporation losses. A distinctive feature of these tanks is the absence of an outlet structure. After the tank is filled up to designed level runoff is automatically diverted to the main waterway as shown in Figure 4. This design saves the cost of an outlet structure besides decreasing the volume of sediment-laden runoff moving through the tank.

An analysis done on the performance of the different collection tanks in meeting the demand for supplemental irrigation, particularly during extended rainless periods for both the monsoon and postmonsoon seasons, revealed the following (Pathak 1980, Miranda et al. 1982):

- Deep dug type tanks in Vertisols showed that in most years they can provide a minimum of 30 mm of supplemental irrigation water for the whole donor catchment area for postrainy season crops. Their relatively low seepage rate of less than 5 mm/day is ascribed to be mainly due to the low saturated hydraulic conductivity.

- The performance of tanks located in Vertic Inceptisols was unsatisfactory. This is due to the high seepage rates of greater than 25 mm/day which is suspected to be caused by the presence of permeable layers in the tank bed and also to the low runoff potential of these soils because of their high infiltration rates.

- Where the seepage rate was less than 15 mm/day in tanks located in Alfisols, it was found that collected water was available for one or two supplemental irrigations for whole of the donor catchment during the rainless periods of the rainy season. However, when seepage rate becomes excessive which can be even greater than 55 mm/day water can be collected but cannot be stored to meet supplemental irrigation needs during the dry spells.

b) Scope for Supplemental Irrigation

Harvested water from the watersheds that is stored in tanks is treated as a scarce commodity. It is used sparingly only for 'life saving' irrigation at the most critical stages of crop growth or for extending the cropping season (Kanwar 1980). In principle, Alfisols which are droughty in nature because they have less water holding capacity but produce more runoff early in the rainy season would benefit more from the application of water during the dry spells occurring during the rainy season. In Vertisols which have higher water retention capacity and generate runoff more towards the latter part of the rainy season when the soil is already fully recharged or nearly saturated, collected runoff water can be put to better use in establishing a sequential postrainy season crop or in irrigating the same crop at the most critical stage, such as at flowering. These simple principles are being translated into decision rules with time at ICRISAT.

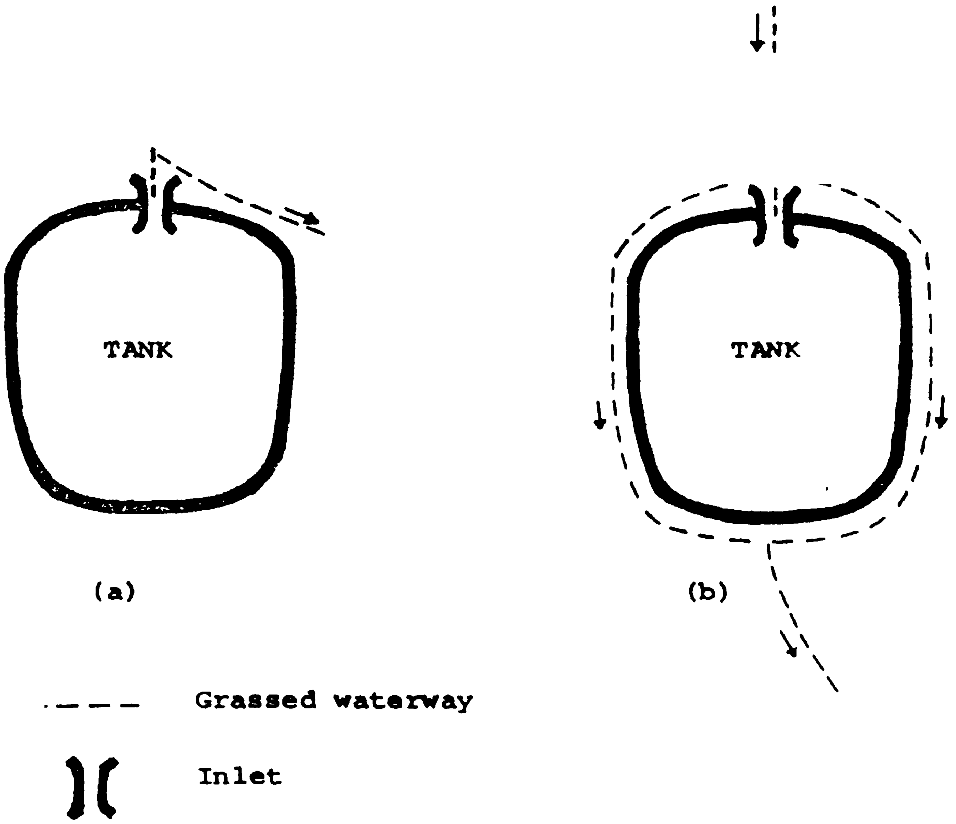


Figure 4 : Alternative arrangements for diverting runoff after filling up of the tank

On operational research plots yields of sorghum and maize on Alfisols were approximately doubled when 50 mm of irrigation was applied during a 30 day drought in late August and early September, 1974. During the following year postrainy season sorghum in Vertisols responded to one supplemental irrigation at the grain filling stage with an increase in yield from 2570 to 3570 kg/ha. In 1979-80 a 60 mm supplemental irrigation to postrainy season sorghum at flowering stage resulted in yield increase from 2950 to 4490 kg/ha. In the 1980-81 postrainy season crop of chickpea, also in Vertisols, the yield was increased from 817 to 1441 kg/ha with one irrigation at flowering stage. It is evident that relatively small amounts of timely water application results in substantial yield increase.

The justaposition of long-term weather records and information relating to water response of various crops will be helpful in deciding scope and developing decision rules for supplemental irrigation.

c) Supplemental Irrigation Through Furrows of BBF System

It has been observed that the application of limited water through furrows becomes difficult where substantial cracking has occurred. We conducted a study during the postrainy season on Vertisols to evaluate the efficiency of shallow cultivation in furrows to facilitate limited water application to chickpea. The treatments were:

T_1 - No supplemental irrigation (control).

T_2 - Uncultivated furrows; one supplemental irrigation through furrows at chickpea flowering stage.

T_3 - Pre-irrigation shallow cultivation (with hand hoes) in the furrows; one supplemental irrigation through furrows at the chickpea flowering stage.

We found that the rate of advance was substantially higher in cultivated furrows than in uncultivated furrows (Fig. 5). The study indicated that pre-irrigation cultivation in cracked furrows enhances irrigation efficiency and results in considerable saving of water without causing any significant difference in chickpea grain yields (Table 5).

d) Low Cost Tank Sealing Technique

Since the success or failure of water harvesting was found to be related with the capacity to keep this water in the tank; tank sealing studies were initiated to solve the problem of high seepage rates. Early studies in small pits at ICRISAT showed asphalt to be promising in controlling seepage (ICRISAT Annual Report1975-76). Asphalt was applied at the rate of 4 lit/m^2. The seepage reduction in Alfisols varied from 97% to 47% when compared with the control (seepage rates for control varied from 24.7 to 50 mm/day). The large variation in seepage reduction is indicative of how uncertain the effectiveness of asphalt was. In Vertisols there was no significant reduction in seepage rates.

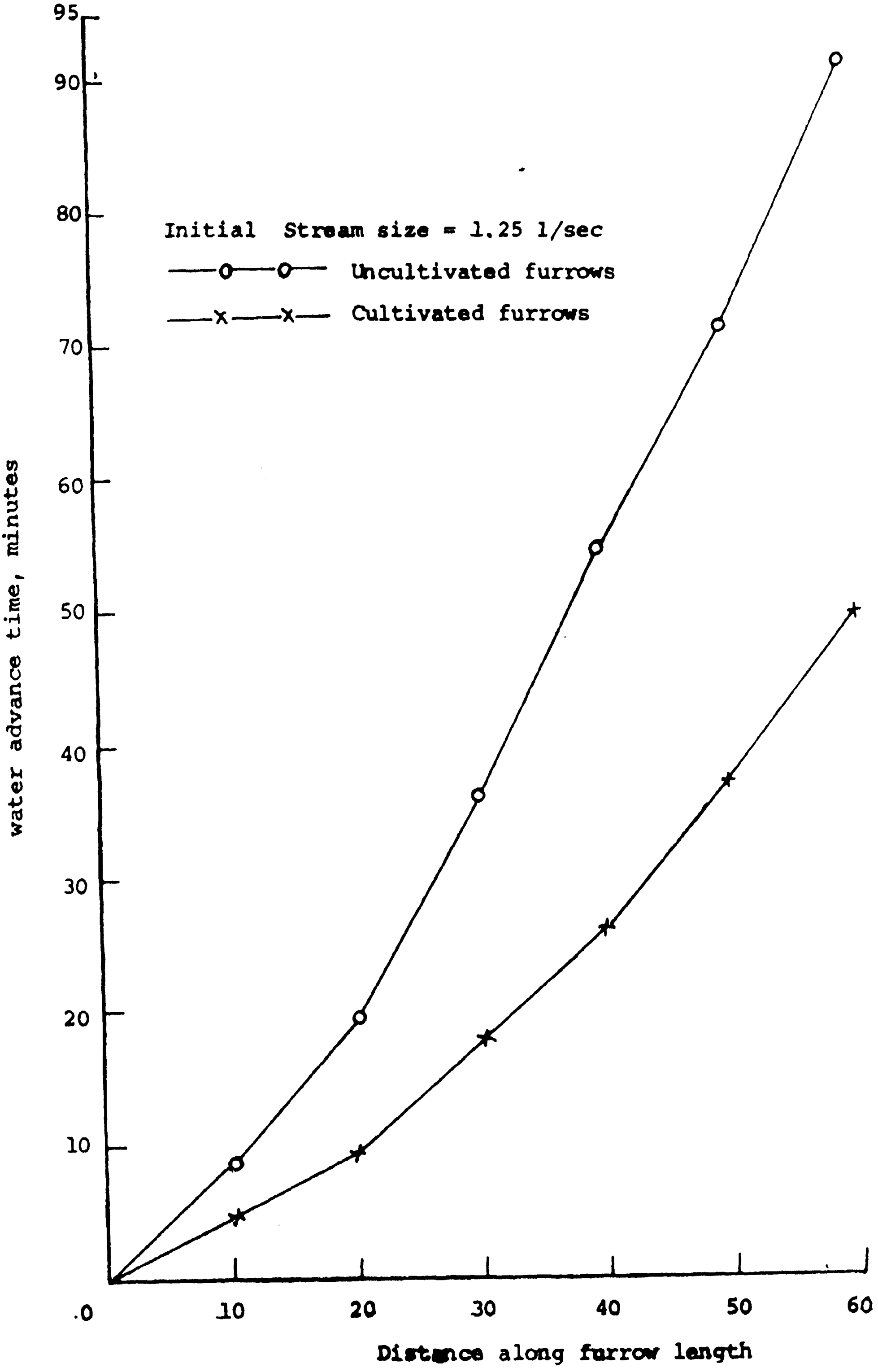


Figure 5 : Effects of cultivation in furrows on water advance

Table 5. Effect of cultivation in furrows on water application and grain yield of chickpea

Treatment	Mean depth of water application (d), mm	Irrigation distribution efficiency[a] (%)	Mean grain yield (Kg/ha)
T_1 - No supplemental irrigation (control)			690
T_2 - Uncultivated furrows; one supplemental irrigation at flowering	63	60	920
T_3 - Cultivated furrow; one supplemental irrigation at flowering	46	71	912
SE			± 19
CV (%)			5.55

[a] The irrigation distribution efficiency values were computed using the equation:

$$\text{Distribution efficiency} = \left(1 - \frac{\sigma}{\bar{d}}\right) \times 100$$

Where

σ = Standard deviation of water application depth along the furrow length

$\bar{d}$ = Mean water application depth

A seepage reduction of about 70% was obtained with a treatment of Na_2Co_3 + straw in Vertisols (ICRISAT Annual Report 1975-76). However, use of straw presented a problem after sometime because, with its decomposition, a porous structure of the lining resulted. In another study, Sharma and Kampen (1977) observed that a lining of silt (15 cm thick) + Na_2Co_3 (0.4 kg/sqm) was successful in cutting down seepage losses by 55%. They reported that the cracking of lining remained the main problem in Vertisols in addition to the necessity of reapplication of salts after 3-5 years.

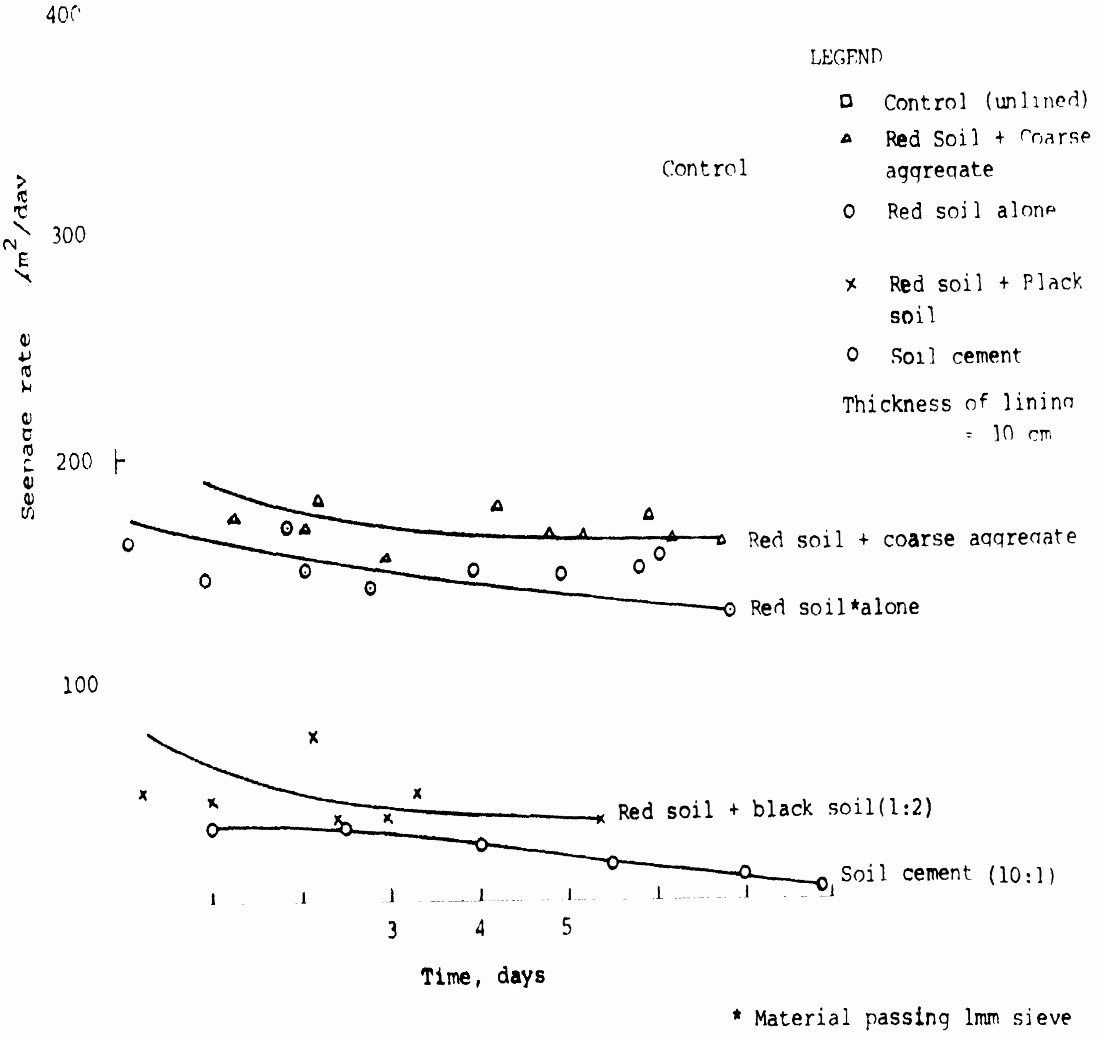
Maheshwari (1981) tried the use of soil dispersants, soil cement lining and improvement of soil gradation as the three basic methods to reduce seepage rates in Alfisols and Vertisols. He observed that soil cement (10:1) and a mixture of red and black soils (1:2) were the two most effective linings for tanks on Alfisols (Fig. 5). The seepage rate was as low as 8.2 lit/m^2/day in soil-cement lined tanks which meant a reduction in seepage of 97.2%. However, cracking was found to occur when the tank was emptied and the lining exposed to the sun increasing the seepage rates when the tank was refilled. We are now attempting to minimize the effect of cracking through provision of expansion joints and filling these joints with asphalt.

7. RUNOFF MODELING

Using measured rainfall and runoff data of several watersheds and standard runoff plots along with associated characteristics, Ryan and Pereira (1978) derived daily rainfall-runoff relationships by multiple regression techniques for Sholapur and Hyderabad regions of India. These empirical relationships have been found to predict runoff satisfactorily on some independent data sets.

A parametric simulation model 'RUNMOD' was developed using the hydrologic data collected at small agricultural watersheds at ICRISAT Center (Krishna 1981). The model needs as inputs: daily rainfall amount, the storm duration or rainfall intensity and pan evaporation. The model characterizes infiltration by only two parameters that are determined through calibration by using a univariate optimization procedure. Once the parameters are determined for a particular land management treatment, they may be applied directly to a similar situation elsewhere for predicting runoff. The flow chart of the model is shown in Figure 7. The various terms used in the flow chart are:

TF - Time function in days, required for soil cracks to close.
MUI - Initial soil moisture in upper zone, mm.
MUX - Total soil moisture in upper zone at field capacity, mm.
MLI - Initial soil moisture in lower zone, mm.
MLX - Total soil moisture in lower zone at field capacity, mm.
RIH - Infiltration parameter -- 'High' rate of infiltration, mm/hr.
RIL - Infiltration parameter -- 'Low' rate of infiltration, mm/hr.
P - Daily precipitation, mm.



* Material passing 1mm sieve

FIGURE 6 : PERFORMANCE OF DIFFERENT LINING TREATMENTS IN ALFISOLS

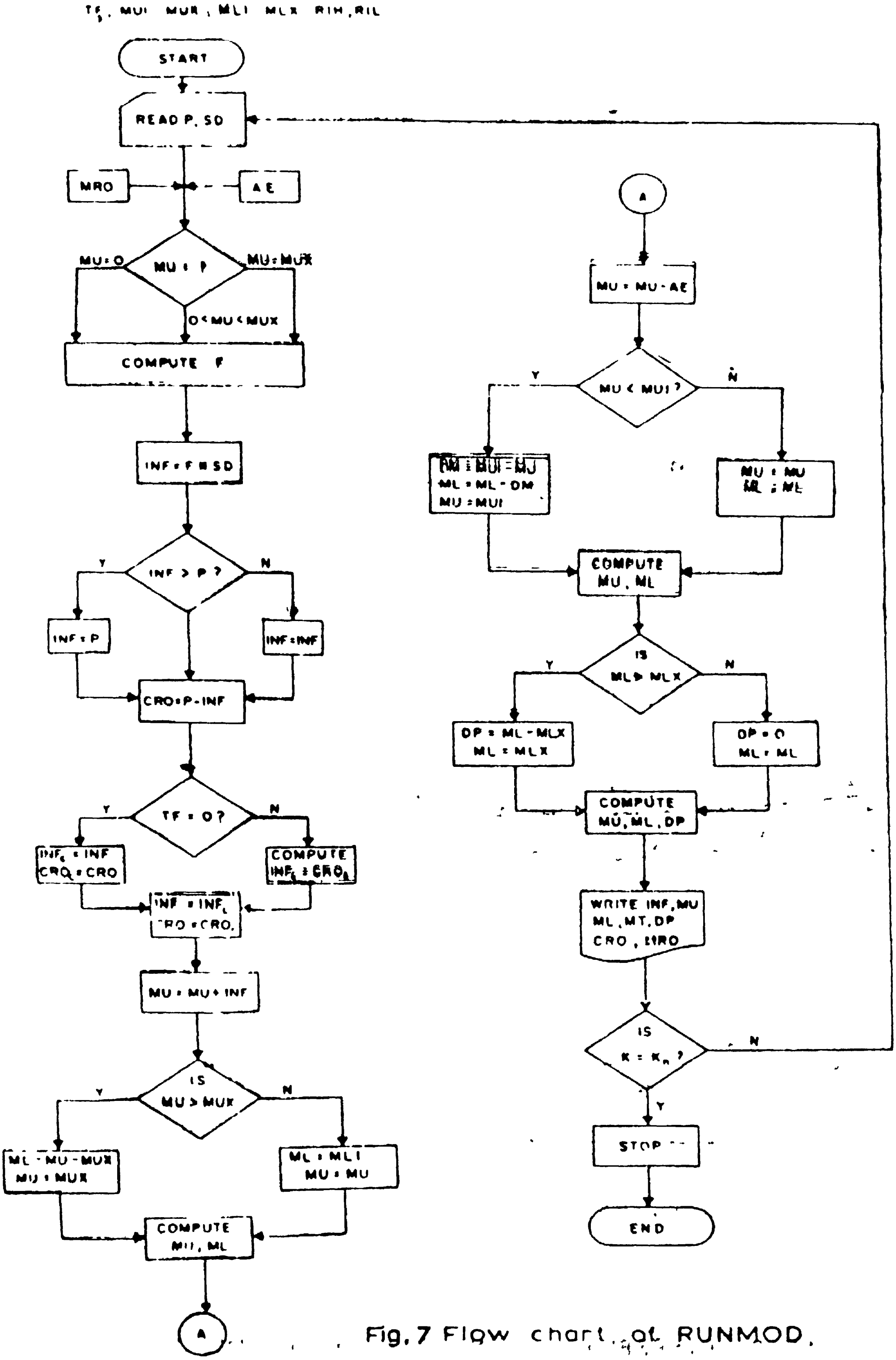


Fig. 7 Flow chart of RUNMOD.

SD - Storm duration, hrs.
MRO - Measured runoff, mm.
AE - Evapotranspiration, mm.
MU - Total soil moisture in upper zone at any given time, mm.
ML - Total soil moisture in lower zone at any given time, mm.
F - Infiltration index, mm.
INF - Amount infiltrated, mm.
DP - Deep percolation, mm.

The model predicts seasonal runoff volume of Vertisol watersheds fairly accurately (ICRISAT Annual Report 1982). This model will now be tried and adapted for Alfisol watersheds. The 'curve number' method of the United States Soil Conservation Service has also shown promising results. These models will be helpful in predicting runoff of ungauged watersheds in different regions for formulating decision rules and for design purposes.

LOOKING AHEAD

Apparently the feedback from the on-farm studies relative to small watershed approach for Vertisol management in India will have a strong bearing on our future research. The encouraging results obtained from the Tadanpally village watershed have given us considerable optimism regarding the applicability and usefulness of our present approach. It seems appropriate to initiate some base line research in Africa to enable us to delineate areas where a technology based on a similar approach will have potential. Research on Alfisols will be focused on testing alternative management approaches primarily at ICRISAT Research Center.

The rainfall-runoff models mentioned in this paper will be tested for different soil and agroclimatic situations. With the help of rainfall-runoff models and hydrologic data, the probability of getting given quantities of water during growing season, and tank failure at varying levels of seepage losses will be studied. The on-going work on tank linings will be continued. Techniques for imporving the efficiency of supplemental irrigation will be investigated.

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ROLE OF SIMULATION MODELS IN YIELD PREDICTIONS - ICRISAT EXPERIENCE IN MODELING SORGHUM GROWTH AND DEVELOPMENT[1]

AKS Huda, MVK Sivakumar, SM Virmani, JG Sekaran, and Sardar Singh[2]

SUMMARY

Complex interactions of weather variables among themselves and with crop and soil make it difficult to predict yields accurately. Process-based, soil and climate driven simulation models are useful in integrating rainfall, evaporative demand, soil water storage, runoff and crop characteristics in order to match crops and cropping systems to available water. The grain sorghum simulation model (SORGF) reported from Texas A & M University was selected for testing and validation to determine its utility for assessing sorghum production in the SAT. A brief description of the model is given. A collaborative multilocation sorghum modeling experiment which was initiated by ICRISAT in the 1979 rainy season to develop a data base to test and improve SORGF has also been briefly discussed. Several subroutines of the model that needed modification for the overall validation of the model in SAT include light interception, phenology, dry matter accumulation and partitioning, soil water and leaf development. These subroutines were revised and the resulting improvements were discussed. The model was used to analyse the soil and climatic data to examine sorghum yield potential for the Magarini Land Settlement Scheme in Kenya. Results suggested that prospects for growing sorghum in both the long rains and short rains are fairly promising in that area. The knowledge gained from sorghum modeling research is being extended to develop growth and development model for pearl millet. The collaborative experiments are being planned to incorporate crop stress factors in both sorghum and pearl millet models. A standard data set that needs to be collected for better interpretation of the experimental results is given.

1. INTRODUCTION

Variations in crop yields between years are associated with many factors which include fluctuations in weather and the management of crop, soil and water. Complex interactions of weather variables among themselves and with crop and soil make it difficult to predict yields accurately. Fluctuations in weather is recognized as one of the most important factors causing yield variations. Therefore, many attempts were made in the past to study the effect of weather variables on crop yield (Fisher 1924,

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[1] Paper for presentation at the IRAT-ICRISAT Workshop on Water Management and Crop Production, Montpellier, France, 3-6 May 1982.

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Stacy et al. 1957, Ram Dayal 1965, Runge 1968, Thompson 1969, and Huda et al. 197 These models which mainly employed correlation and regression methods are regarded as between-year models and require historical yield and weather data. The models assume that the current year is part of a composite population of the base period years which provides expressions for yields as a function of weather variables.

Application of between-year models has not been successful because of two primar reasons. First it is hard to obtain reliable weather and related crop yield data for a sufficiently long period of years. Secondly, the information on the manner in which variation in weather factors during a given crop season affects growth and development is not incorporated adequately in these models. Therefore, much emphasis has now been given to models which may be termed as within-year models where growth of field grown plants is simulated in response to daily changes in environmental conditions A crop simulation model predicts the final yield but also provides quantitative information on intermediate steps including daily weights of different plant parts which can be verified by experimentation. Such models are developed by considering the physical and physiological principles that govern the plant growth; these to a large extent cannot be location specific. Moreover, as opposed to the between-year models, time series data are not required to build these models.

Process based, soil and climate driven simulation models are useful in integratin rainfall, evaporative demand, soil water storage, runoff, and crop characteristics in order to match crops and cropping systems to available water. Crop simulation models would help in assessment of the crop production and the quantification of associate risks. These models can be used to develop methodologies for broad-scale first order screening of environments for crop production.

The utility of crop simulation models as a research tool, the methods and limitations of developing such models were discussed by Huda and Virmani (1981). The objective of this paper is to enumerate the progress made by ICRISAT in sorghum modeling research and propose future plans of work.

2. APPROACH AND METHODOLOGIES

Systems simulation approach using crop-weather models is useful in integrating knowledge from different components of interdisciplinary research for identifying alternativ management practices that are most likely to be successful. At the International Workshop on the Agroclimatological Research Needs of the Semi-Arid Tropics held at ICRISAT Center, India in 1978, modeling approaches and minimum data requirements were discussed by Huda et al. (1980). One recommendation of the workshop was that growth model available in the literature for an ICRISAT mandate crop should be selecte and data sets from well defined, diversified agroclimatic locations should be collected to test and update the existing model for adoption to SAT locations.

Models for several crops are available in the literature e.g., maize (Duncan 1975), soybean (Curry et al. 1975), sorghum (Arkin et al. 1976), cotton (Baker et al. 1976), and wheat (Maas and Arkin 1980).

Sorghum being an important component of the cropping system in the SAT, received our initial attention. We believe that the knowledge and experience so gained could be extended subsequently to other crops. The only growth model available for sorghum is the SORGF model reported by Arkin et al. (1976). The model was selected for testing and validation to determine its utility for assessing sorghum production in the SAT. The input data requirement is relatively simple and the model is not as complex as the other crop growth models.

a) Brief Description of SORGF

A detailed description of SORGF model has been given by Maas and Arkin (1978) and the utility was discussed by Huda and Virmani (1980). The model requires daily radiation, maximum and minimum temperature, and precipitation as weather input data. The initial plant and soil information needed includes date of sowing, depth of sowing, row spacing, plant density, potential number of leaves and their maximum size, maximum water holding capacity of the soil and available soil water at sowing. Different phenological stages including emergence, panicle initiation, anthesis and physiological maturity are simulated. The potential dry matter is computed from radiation intercepted and the net dry matter is estimated by accounting for temperature and moisture stress. The final grain yield per unit area is calculated by multiplying plant density with the grain weight per plant at maturity.

b) Collaborative Multilocation Sorghum Modeling Experiment

To develop a data base to test and improve SORGF for its application in the semi-arid tropics (SAT), a collaborative multilocation sorghum modeling experiment was initiated in the 1979 rainy season by ICRISAT in cooperation with several research centers in India and abroad (Table 1). To ensure the uniformity in data collection across the locations, a manual describing the minimum data to be collected and the method of data collection was prepared and circulated to all cooperators. During the past three years, scientists from different disciplines have collected data on soils, crops, weather and management factors. At a cooperators' meeting held at the ICRISAT Center, 2-4 April 1980 (Huda et al. 1980), the model was evaluated using some initial data collected and several subroutines in SORGF were identified which needed modification so that the model could provide reasonably accurate simulations. These subroutines include light interception, phenology, dry matter accumulation, and partitioning, soil water, and leaf development.

A cooperative consultancy program was established between ICRISAT and Texas A & M University where SORGF was initially developed to exchange data and revise some of the subroutines. Sivakumar (1981) reviewed subroutines on light interception, dry matter accumulation and soil water and suggested revisions. Huda (1982) reviewed subroutines on phenology, dry matter partitioning and leaf development and assessed the improvements made in SORGF with recent revisions.

Table 1. Summary of collaborative multilocation sorghum modeling field studie

Location	Year	Season	Genotypes	Moisture Treatment	Latitude (°N)
ICRISAT*	1979	Rainy	CSH-1, CSH-6 SPV-351	Rainfed	17' 27'
	1979	Postrainy	CSH-8, M-35-1	A and B	
	1980	Rainy	CSH-1, CSH-6 SPV-351	Rainfed and A	
	1980	Postrainy	CSH-6, CSH-8 M-35-1	A and B	
Coimbatore	1980	Postrainy	CSH-8	A	11' 00'
Delhi	1979	Rainy	CSH-1, CSH-6	Rainfed	28' 35'
	1980	Rainy	CSH-1, CSH-6	Rainfed and A	
Hissar	1979	Rainy	CSH-1, CSH-6	Rainfed	29' 10
	1980	Rainy	CSH-6	Rainfed and A	
Khon Kaen (Thailand)	1979	Rainy	KU-300	Rainfed	16' 26'
	1980	Rainy	Hegari	Rainfed	
Ludhiana	1980	Rainy	CSH-1, CSH-6	Rainfed	30' 56'
Parbhani	1979	Rainy	CSH-1, CSH-6	Rainfed	19' 08'
		Postrainy	CSH-8, M-35-1	Residual moisture	
	1980	Rainy	CSH-1, CSH-6	Rainfed	
		Postrainy	CSH-8	A	
Pune	1979	Rainy	CSH-1, CSH-6	Rainfed	18' 32'
		Postrainy	CSH-8, M-35-1	A	
	1980	Rainy	CSH-1, CSH-6	Rainfed	
		Postrainy	CSH-8	A	
Rahuri	1979	Rainy	CSH-1, CSH-6	Rainfed	19' 24'
		Postrainy	CSH-6, CSH-8 M-35-1	Residual moisture	
	1980	Rainy	CSH-1, CSH-6	Rainfed	
		Postrainy	CSH-8, M-35-1	A	
Sholapur	1979	Postrainy	CSH-8, M-35-1	Residual moisture	17' 40'

A = adequately watered; B = Water stressed.

*both Vertisols and Alfisols.

3. FINDINGS

The algorithms of light interception, phenology, total dry matter accumulation and its partitioning to grain, and leaf senescence have been revised. The improvements resulting from the revisions made are compared in each case e.g., light interception and phenological estimates etc. with the original SORGF model. Simulated dry matter and grain yield are compared with the field data. A detailed account of the revisions made in the model is discussed by Huda et al (1982).

a) Light Interception

The light interception portion of the model simulates the relative quantum flux intercepted by a single plant. Intercepted Photosynthetically Active Radiation (PAR) is calculated on an hourly basis following a Beer's law relationship using solar radiation and light transmission values. Hourly solar radiation is computed from the input solar radiation and by accounting for the number of hours of sunlight for any day which is calculated as a sine function of the local solar time and day length. Examination of our data showed that model computation of solar declination and day length are accurate resulting in sufficiently accurate estimation of hourly solar radiation. The quantum flux density (PAR) in Einsteins m^{-2} day^{-1} is estimated in SORGF from the energy flux density (RS) in cal cm^{-2} day^{-1} as

$$PAR = RS\ (0.121)$$

However, our results using measured data on PAR and RS for extended periods of time indicated that the constant relating PAR to solar radiation (RS) should be altered. In the revised version, PAR is thus calculated as 0.09 times RS.

Light transmission is calculated from the relationship of extinction coefficient and maximum light transmission using information on row spacings and LAI. An examination of the computed and measured light transmission for different row spacings showed that the model was overestimating light-transmission, especially at low levels of canopy light transmission. The model breaks down for row spacings greater than 137 cm because the computed light transmission exceeds 100 percent. Thus the functions for estimating extinction coefficient and maximum light transmission were revised.

Comparisons of predicted and measured light transmission for 45 cm sorghum rows using the data sets collected at ICRISAT Center are shown in Figure 1. Data points show that the revised equations predict light transmission within 15 percent limit of the measured PAR interception.

b) Phenology

Accurate simulation of phenological events is important because the stage of development determines the daily dry matter partitioning to various plant parts. The period from anthesis to physiological maturity is underestimated by SORGF. In SORGF, the grain filling period is dependent upon the time taken to anthesis. The period from emergence to panicle initiation is overestimated by SORGF particularly in lower latitudes (e.g. ICRISAT Center, 17°N). This overestimation appears to be a result

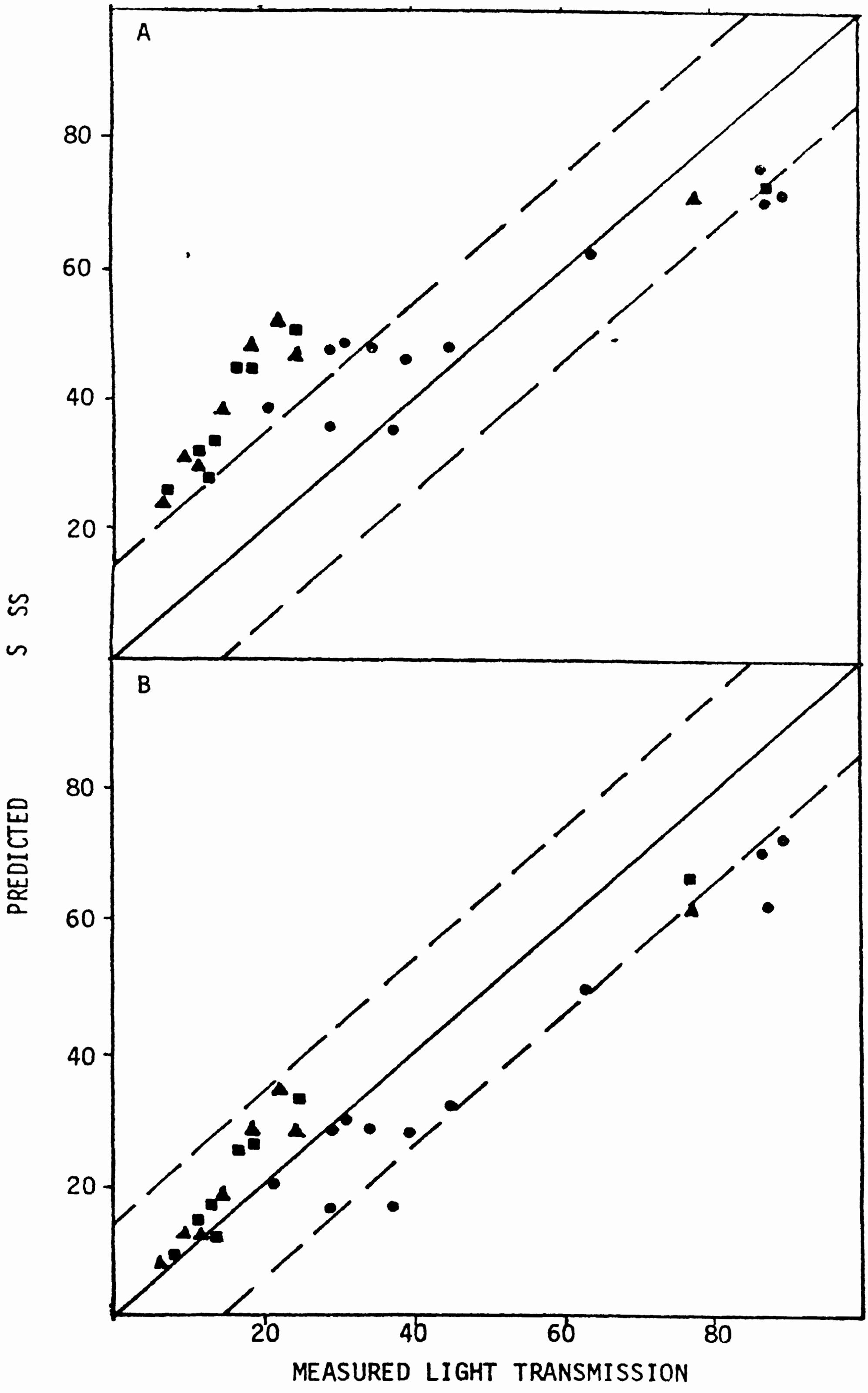

Figure 1. Relationship between measured and predicted light transmission under 45 cm sorghum rows according to (A) SORGF and (B) Revised equations (Symbols represent data from different growing seasons)

New algorithms were developed based on daylength and temperature effects to determine three stages of sorghum development as defined by Eastin (1971). These stages are:

GS1 = The time from emergence to panicle initiation.
GS2 = The time from panicle initiation to anthesis.
GS3 = The time from anthesis to physiological maturity.

These algorithms were used first against the 40 field studies from which these relations were derived. The root mean square errors (RMSE) for predicted days to the three stages were compared with simulations by SORGF and revised algorithms (Table 2). The RMSE was considerably reduced for all three stages using the revised algorithms.

These algorithms were tested against 10 independent field data sets. The RMSE for SORGF and the revised algorithms are given in Table 3. The RMSE for all the three growth stages was considerably reduced using the revised algorithms.

c) Dry Matter Accumulation and Partitioning

In SORGF potential photosynthate is calculated from intercepted photosynthetically active radiation (PAR). Net photosynthate is computed after accounting for the water and temperature stress as well as for respiration. Using the approach of Gallagher and Biscoe (1978) and Stapper and Arkin (1980), a simpler relationship for calculating daily dry matter production from intercepted PAR was developed. From measured data over several growing seasons it was computed that potentially a total dry matter of 2.5 gm can be produced per each Mega Joule of PAR absorbed when water and temperature stress do not occur. From the daily potential dry matter, actual dry matter increase is estimated as a function of temperature and water stress.

Partitioning of total dry matter (TDM) to leaf, culm, head + grain and grain was studied by using data collected at weekly intervals from 27 field studies conducted at ICRISAT. TDM at anthesis and maturity was not significantly different between hybrids and varieties (Table 4). The percent of TDM partitioned to leaf was not significantly different between hybrids and varieties. The proportion of TDM accumulated in the culm was significantly higher in the varieties at both anthesis and maturity. Dry matter partitioned to grain as percent of TDM was higher in hybrids (0.45) compared to varieties (0.32). These data confirm that hybrids are more efficient than varieties in translocating dry matter to grain.

d) Soil Water

In SORGF daily available water for the entire soil profile (single layered) is computed after Ritchie (1972) using information on initial available soil water, available water holding capacity, rainfall/irrigation, and evaporative demand. Potential evaporation below a plant canopy (Eos) is calculated after computing potential evaporation from bare

Table 2. Comparison of root mean square error for predicted days to different growth stages for 40 field studies.

Stages	SORGF	Revision
GS1	7	3
GS1 + GS2	7	5
GS1 + GS2 + GS3	19	4

Table 3. Comparison of root mean square error for predicted days to different growth stages for 10 independent field study data sets.

Stages	SORGF	Revision
GS1	7	4
GS1 + GS2	7	6
GS1 + GS2 + GS3	18	3

Table 4. Total dry matter and percent partitioned to leaf, culm, head + grain and grain at three growth stages for hybrid and variety (Date pooled over seasons and moisture treatments, n= 27).

	Panicle Initiation		Anthesis		Physiological maturity	
	Hybrid	Variety	Hybrid	Variety	Hybrid	Variety
Leaf	0.64 a	0.64 a	0.25 a	0.22 a	0.11 a	0.12 a
Culm	0.36 a	0.36 a	0.57 b	0.66 a	0.32 b	0.45 a
Head + Grain			0.18 a	0.12 b	0.57 a	0.43 b
Grain					0.45 a	0.32 b
Total dry matter (g/plant)	1.3 b	2.5 a	32.0 a	43.0 a	65.0 a	73.0 a

Means with different letter are significantly different.

soil (Eo) and using LAI values. Eo is calculated in the model using the Priestley-Taylor (1972) equation which requires net radiation as input data. Net radiation is computed from albedo, maximum solar radiation reaching the soil surface (Ro), and sky emissivity. Ro in the SORGF model was calculated using a site-specific sine function. This function was revised to enable the computation of Ro for any latitude. Open pan evaporation and Eo estimated are compared in Figure 2. This change resulted in improved estimates of Eo as can be seen in Figure 2.

e) Leaf Area

Leaf area is overestimated by SORGF, particularly in the grain filling period. Revisions were made in the leaf senescence algorithms. Senescence is now accounted for after the expansion of 7th leaf instead of the 11th leaf as suggested in SORGF. Leaf area at maturity is estimated as 50 percent of the total leaf area per plant obtained at anthesis.

f) Simulation Comparison

The revised algorithms discussed earlier have been incorporated in SORGF. Simulation results of total dry matter and grain yield are compared with observed data from 27 ICRISAT field studies (Figs. 3 and 4) and for 55 field studies pooled from all cooperating centers (Figs. 5 and 6). The correlation coefficient (r) and the RMSE values for grain yield and total dry matter are given in Table 5.

g) Model Applications

First approximation answers to questions on sorghum yield potential can be generated by this model using climate and soil information. Answers to questions about the sorghum yield potential and to determine the optimum crop duration period matching with the water availability are sought by the Magarini Land Settlement Scheme in Kenya. May et al. (1981) used this model to delineate the cumulative probability distributions of simulated grain yields in Kenya for optimum sowing dates chosen from the rainfall probability analysis. An example of such analysis is given in Figure 7 for two sowing dates at Marafa for the period of 1937-80. This figure indicates that more than 5000 kg/ha sorghum yield can be obtained under adequate management practices in 50 percent of these years. Analysis of the soil and climatic data from different locations of the project area suggest that prospects for growing sorghum in both the long rains and short rains are fairly promising.

Arkin and Dugas (1981) used this model to determine the feasibility of sorghum ratooning in Texas. They constructed a 40-year (1939-78) cumulative probability distribution of simulated ratoon yields for 0, 5, 10, and 15 cm of available soil water (ASW) at the beginning of the ratoon crop (Fig. 8). With 15 cm of ASW at the beginning of the ratoon crop, the probability of producing a 1500 kg/ha or more grain yield for a ratoon crop was about 80%. The profitability of ratoon cropping in Temple, Texas is dependent on soil moisture conditions at the start of the ratoon crop each year.

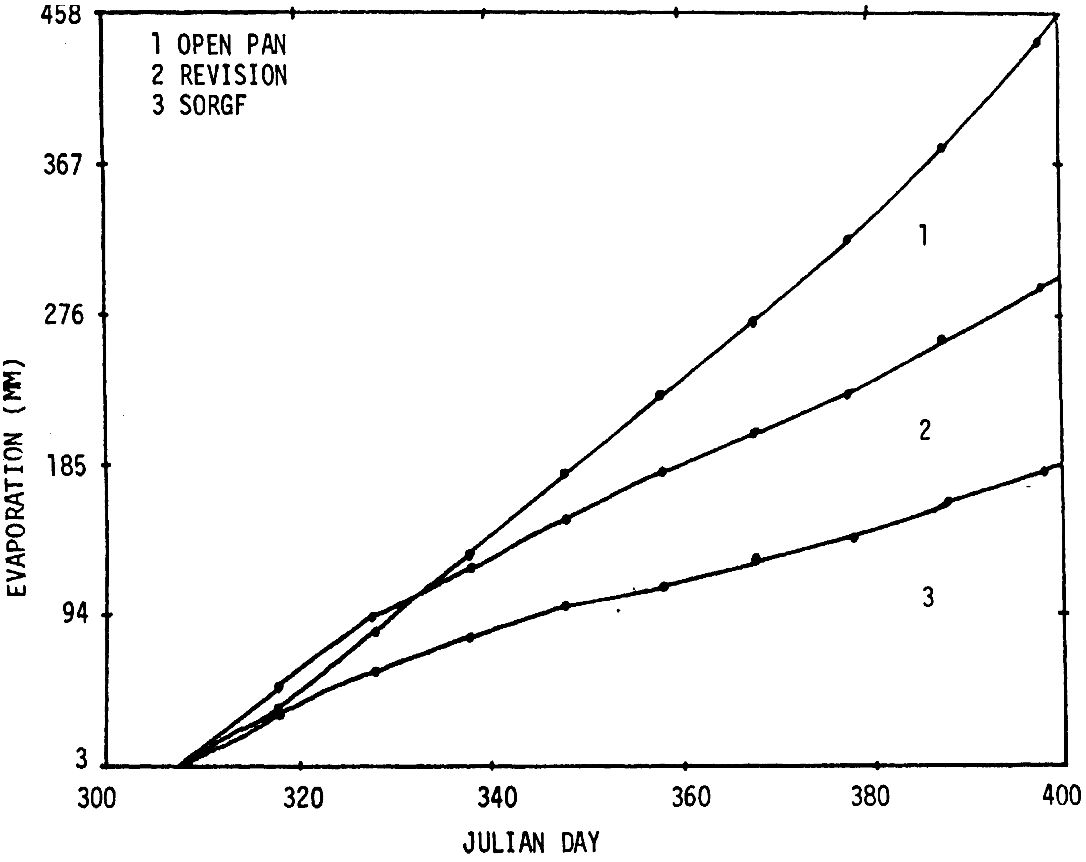

Figure 2. Plot of cumulative evaporation from the bare soil (E_0) during 1978 at ICRISAT research center according to SORGF and the revised equation. Open pan evaporation is presented for comparison.

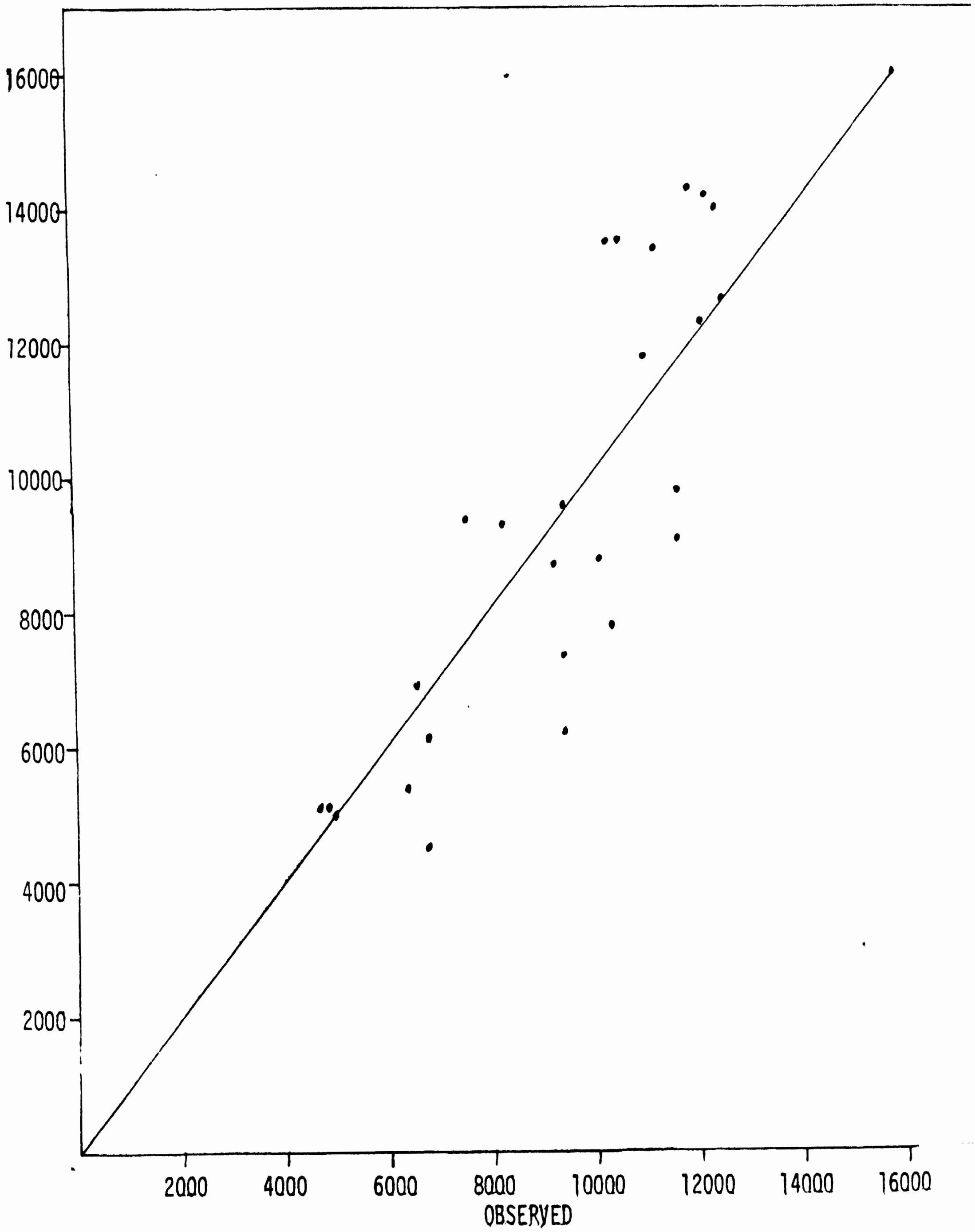

Figure 3. Relationship between observ d and simulated total dry matter (kg/ha) of Sorghum according to revised SORGF model for ICRISAT field data (n = 27)

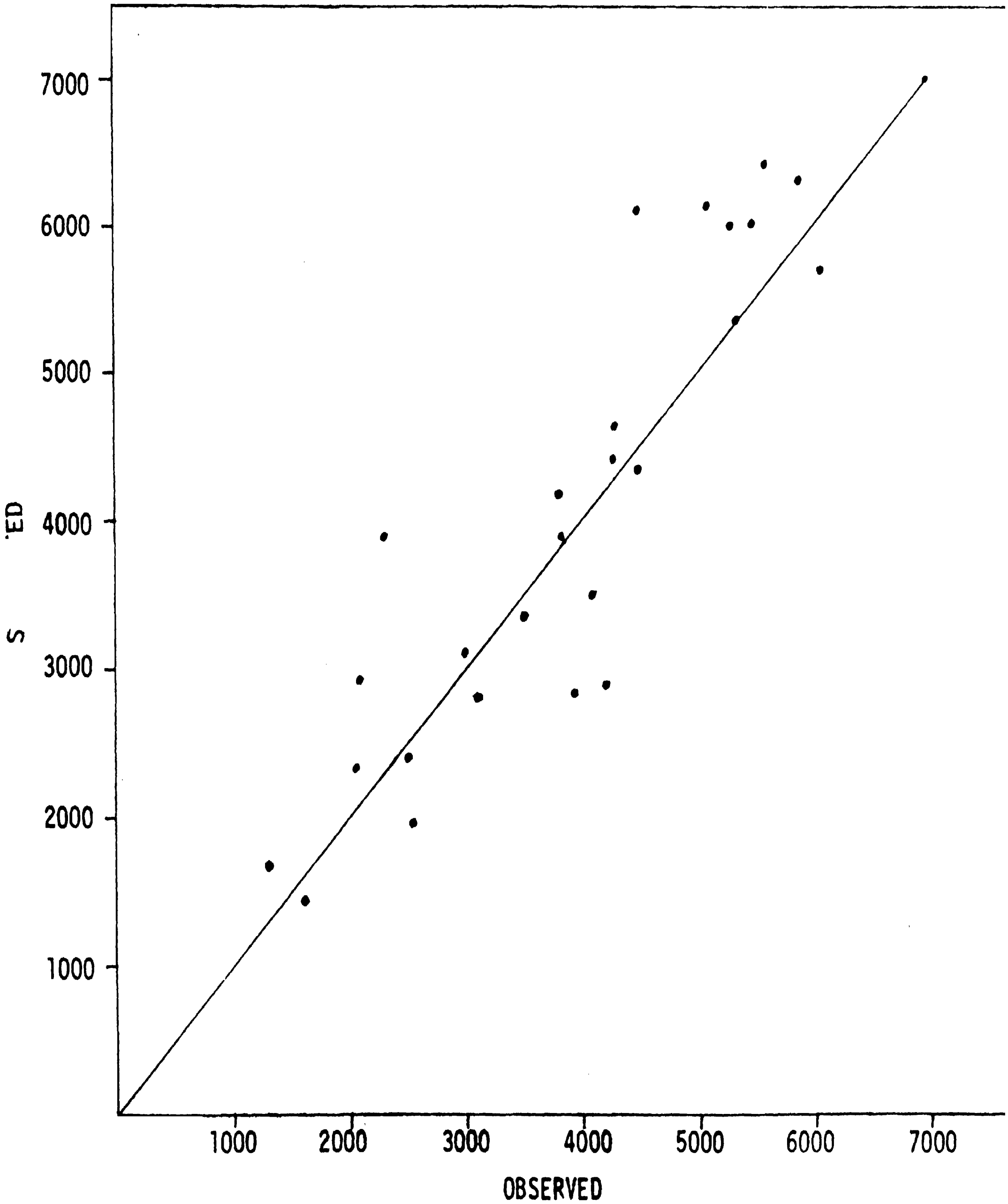

Figure 4. Relationship between observed and simulated grain yield (kg/ha) of sorghum according to revised SORGF model for ICRISAT field data (n = 27).

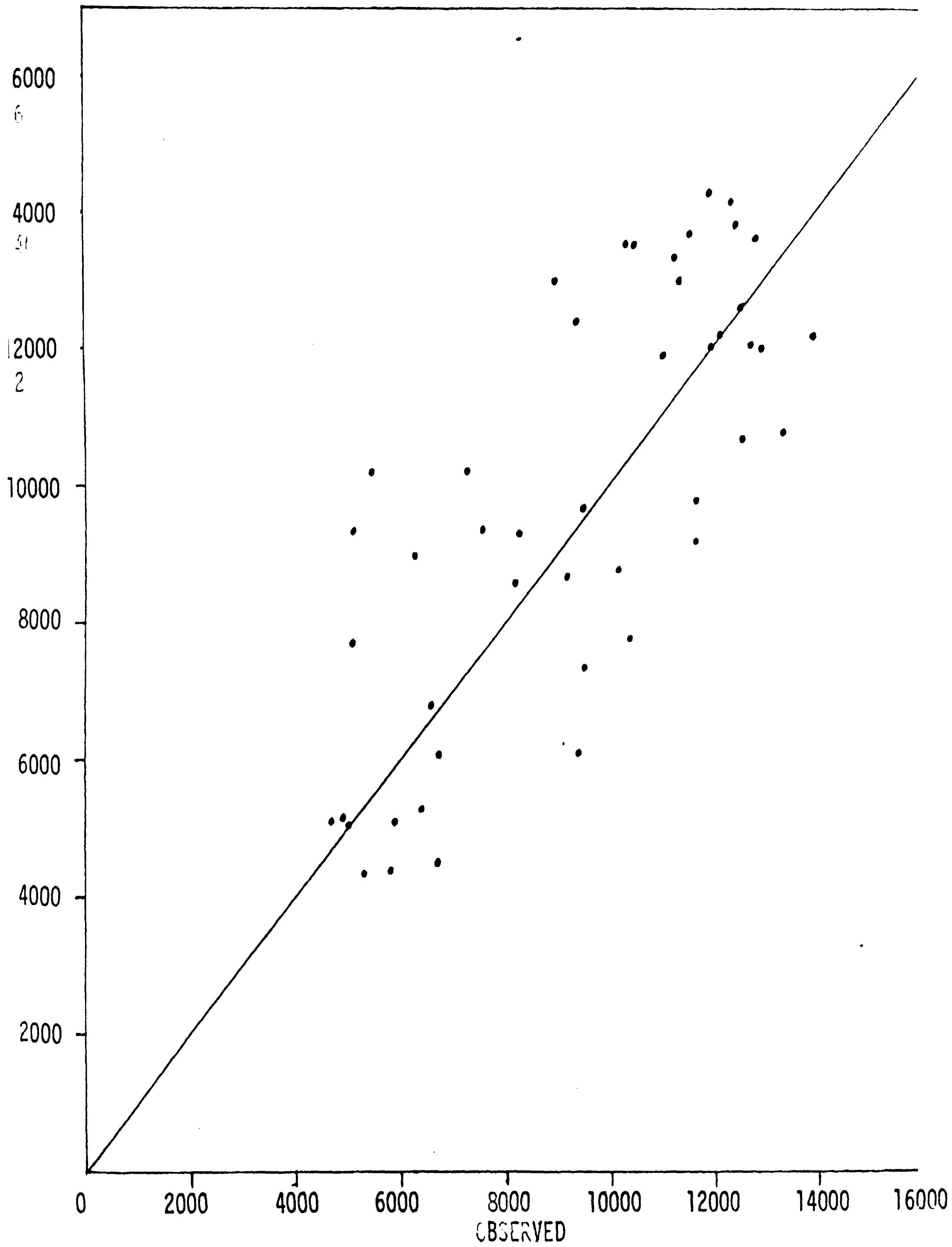

Figure 5. Relationship between observed and simulated total dry matter (kg/ha) of Sorghum according to revised SORGF model for pooled data (n = 47)

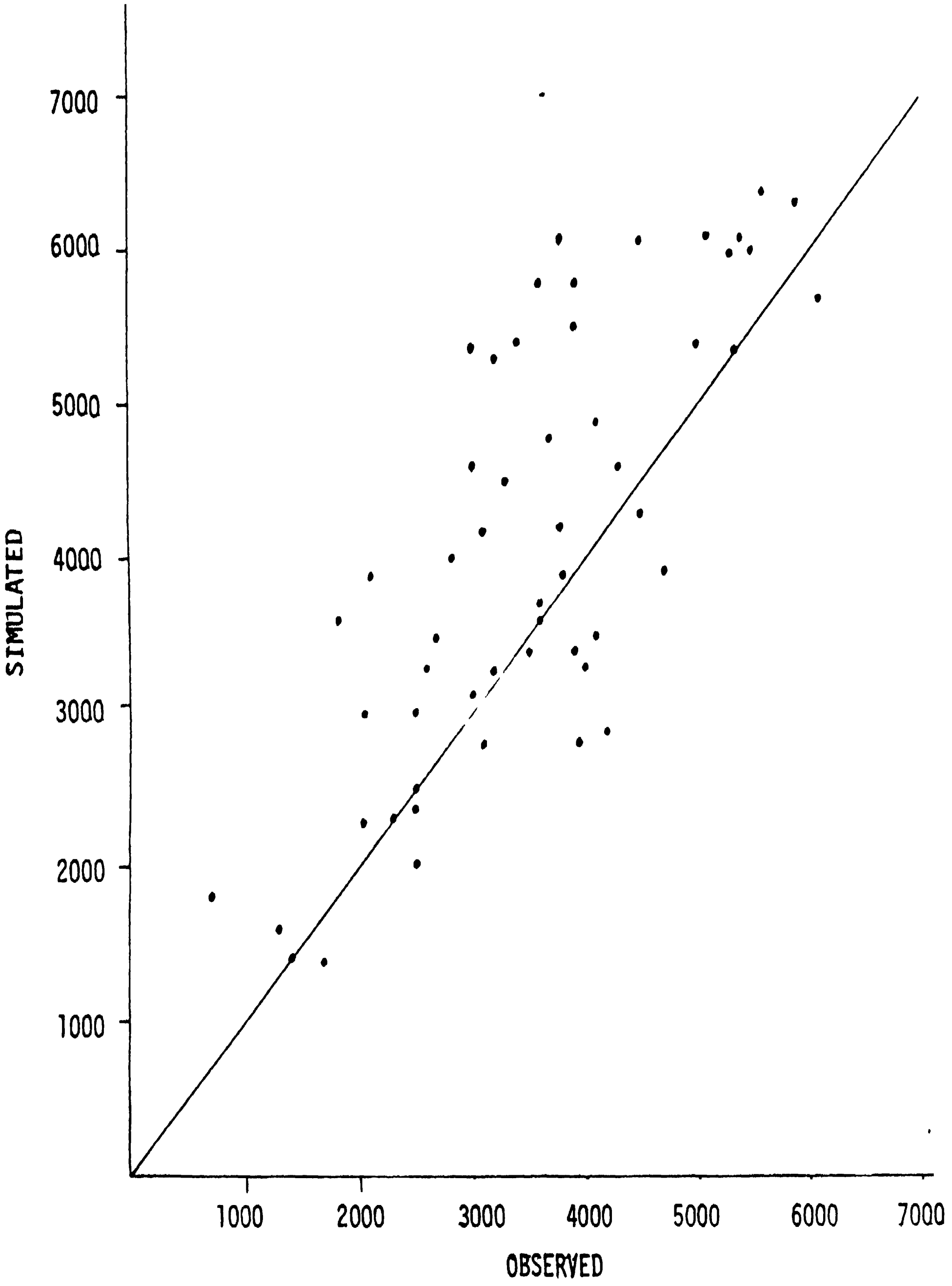

Figure 6. Relationship between observed and simulated grain yield (kg/ha) of sorghum according to revised SORGF model for pooled data (n = 55).

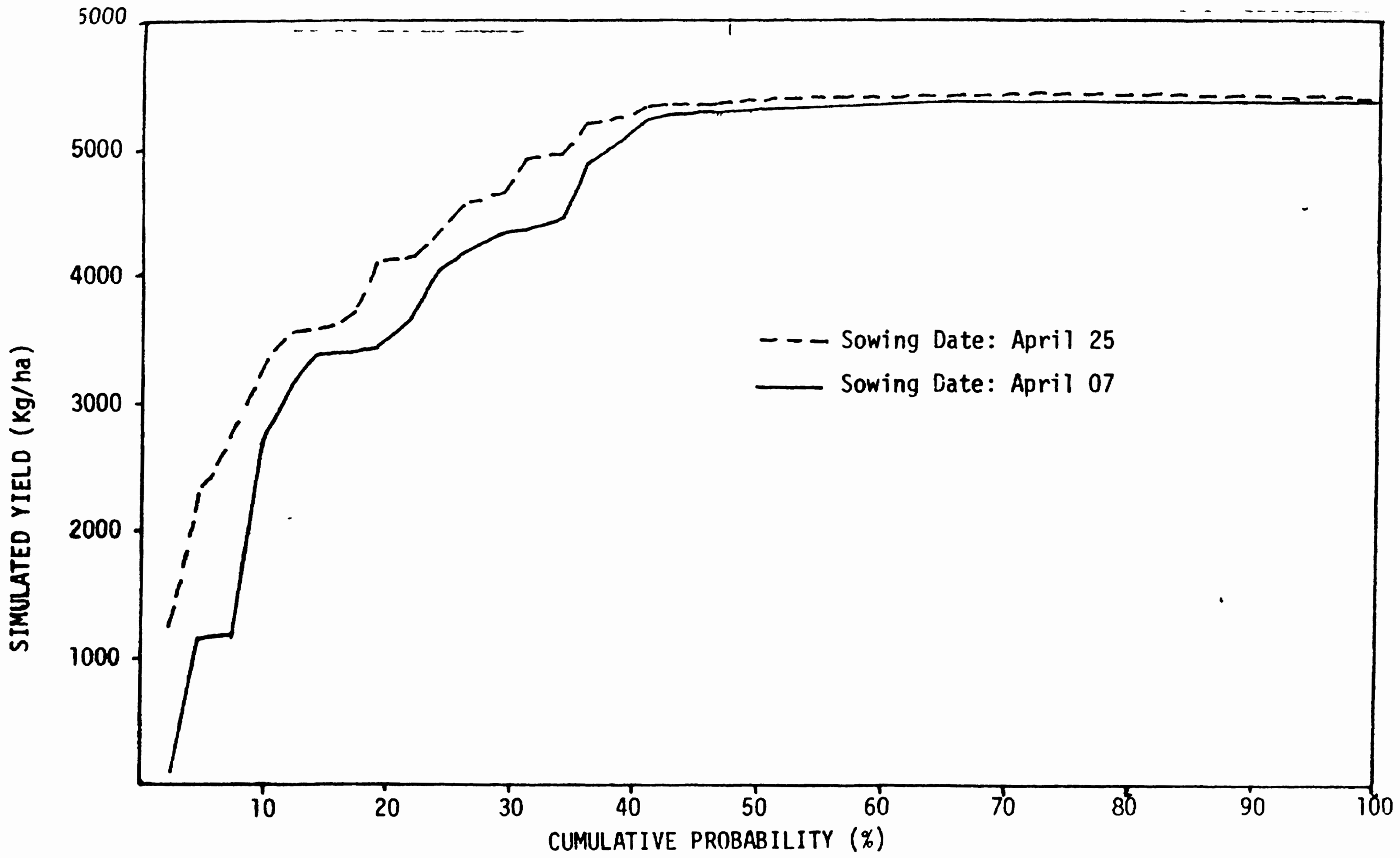

Figure 7: Cumulative probability distribution of simulated grain yield (kg/ha) of sorghum according to revised SORGF model for two sowing dates at Marafa (KFNYA) from 1937-1980.

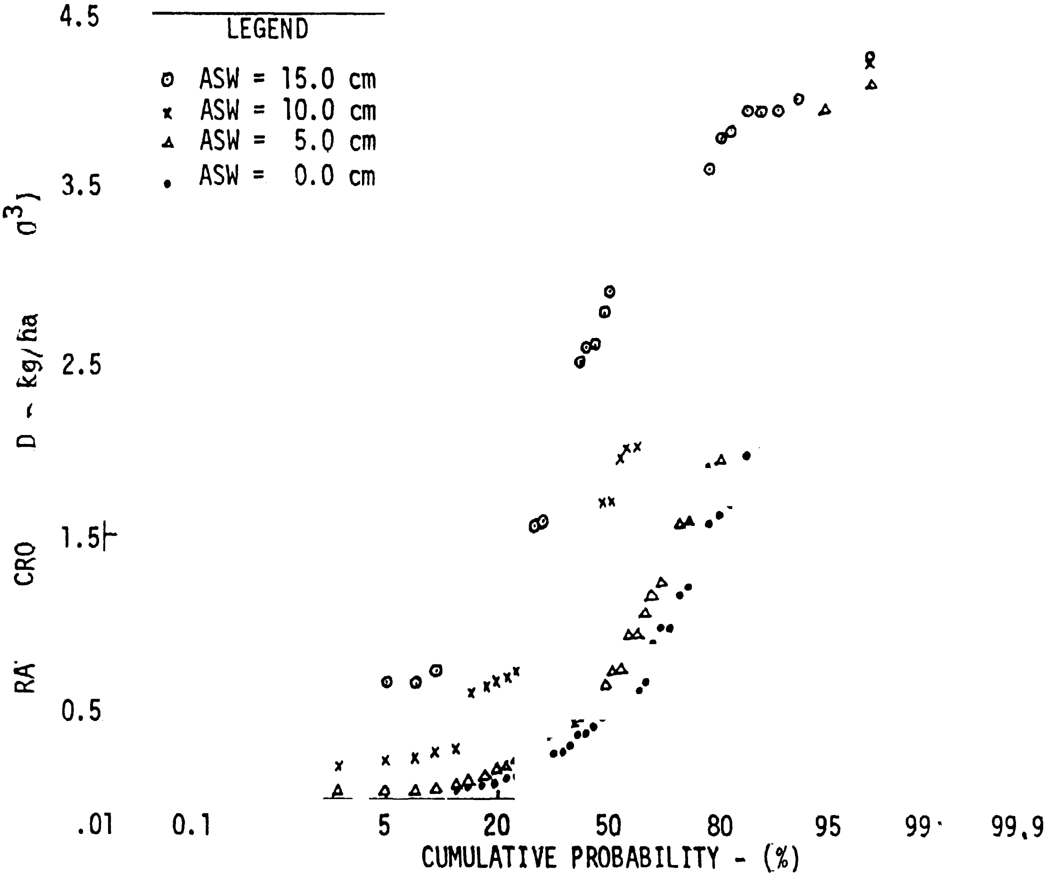

Figure 8. Cumulative probability distribution for simulated ratoon grain yields (kg/ha) of sorghum according to SORGF model from 1939-1978 at four different levels of initial available soil water in a soil of 15 cm available water holding capacity in Temple, Texas. (After Arkin and Dugas, 1981).

Table 5. Correlation coefficients and root mean square errors for observed and simulated grain yield (kg/ha) and total dry matter (kg/ha).

	No. of observations	Correlation coefficient	Root mean square error
Grain yield (ICRISAT)	27	0.91	643
Grain yield (pooled)	55	0.78	1068
Grain yield (cooperating centers)	28	0.76	1373
Total dry matter (ICRISAT)	27	0.83	1798
Total dry matter (pooled)	47	0.76	2101
Total dry matter (cooperating centers)	20	0.75	2502

LOOKING AHEAD

Our experience with the sorghum simulation model over the past four years gave us useful leads to examine alternative management strategies and extend the knowledge to other crops. We will continue our efforts:

- To extend knowledge in developing growth models for other crops of ICRISAT mandate. Pearl millet which is the second cereal crop of our mandate was obviously the next choice. Efforts have been initiated by the Farming Systems Research Program in cooperation with the pearl millet improvement program at ICRISAT to develop a growth and development model for pearl millet. Experiments are being conducted from the 1981 rainy season to collect standard data sets on crop, soil and weather to achieve this objective.

  The framework of the sorghum model with some modifications can be utilized to produce a pearl millet growth model. The modifications include the change of individual leaf concept as is done in SORGF to leaf area index. The development and incorporation of a tillering subroutine is very important. A suggested flow chart for pearl millet growth and development is given in Figure 9.

  Collaborative experiments are being designed to study light interception, water use, phenology, tillering habit, dry matter accumulation, and partitioning of pearl millet under both Indian and West African conditions. Experiments are also planned to study the effects of method of planting e. g. row (practised in India) versus hill (practised in West Africa) on the growth and development of pearl millet.

- To use the revised sorghum model in developing a methodology for first order screening of different environments for their crop production potential.

- Sorghum yield simulations are presently made assuming that crops are raised under adequate nutrient supply, weed free, insects/disease free conditions. Algorithms addressing these questions should be developed and incorporated in the model for yield simulation under the real world situations. Thus collaborative experiments need to be planned for quantifying the stress factors (moisture, nutrient, biotic etc).

- Suggestions are made to collect data from the literature and unpublished information from the previous experiments conducted elsewhere in order to develop and test sorghum and pearl millet growth models. A list of standard data set that needs to be collected for developing and testing crop simulation models is given in Table 6.

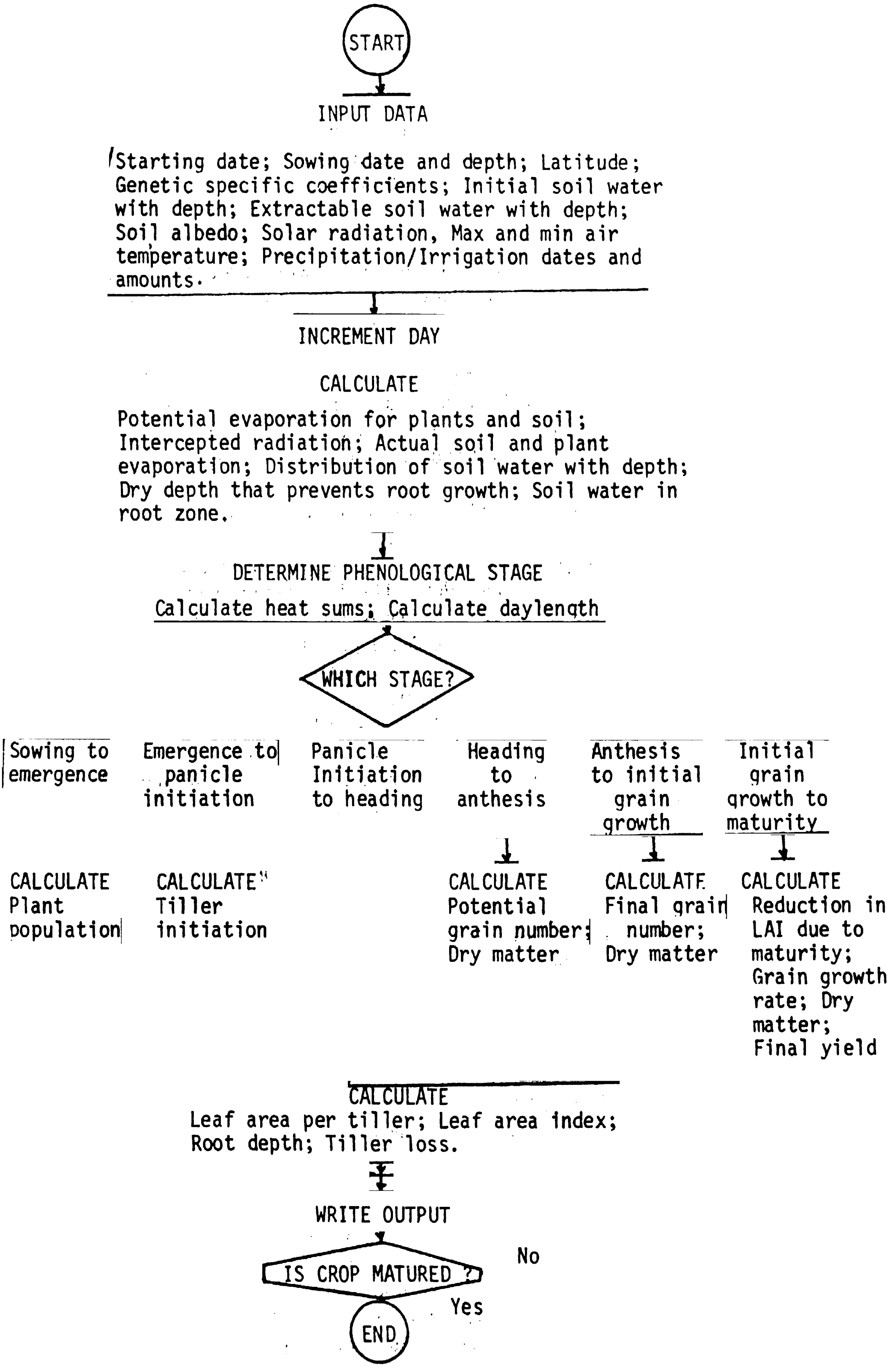

Figure 9. A suggested flow chart for Pearl Millet growth and development model (after USDA-SEA winter wheat ecological model).

Table 6. A list of standard data set that needs to be collected for developing and testing crop simulation models.

Planting Data. Date of planting; depth of planting; dates of emergence, panicle initiation, flowering, and physiological maturity; row width, and plant density.

Crop Data. Genotype, leaf area index, total dry matter, and grain yield.

Daily Climatic Data. Maximum temperature, minimum temperature, solar radiation, rainfall, and open pan evaporation.

Soil Data. Available water holding capacity, and initial available water content.

Location Data. Latitude.

Additionally, these data are useful for interpretation of the experimental data collected across diverse locations.

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TRANSFER OF WATERSHED TECHNOLOGY TO THE FARMS
FARMING SYSTEMS EXPERIENCE[1]

L.D. Swindale[2]

In this paper the progress being made in applying the technology we have developed for better management of the deep black soils of India, and the new concepts and methodologies we are developing for farming systems work in the future are highlighted.

The Governing Board of ICRISAT some years ago set up a standing subcommittee known as the Technology Transfer Committee. This committee examines new technologies developed by the Institute's scientists and recommends to the Board those that appear ready for dissemination. In March 1980 the Technology Transfer Committee discussed the results of 7 years of farming systems research at ICRISAT. Following this discussion the Committee reported to the Governing Board that the strongest case for transfer was undoubtedly with the technology for the deep and medium-deep black soils, or Vertisols. It suggested that operational research and pilot studies might be undertaken.

The Governing Board then proposed that a seminar be developed with top-level policy makers in India to acquaint them with the technology. It was suggested by Dr. M.S. Swaminathan, Member, Planning Commission, that the Government and ICAR might cosponsor the seminar to discuss not only ICRISAT's work, but also related work of the All India Coordinated Research Program in Dryland Farming. In the Board's discussions it was clarified that ICRISAT itself would not undertake pilot studies but would assist and support national programs that did. Dr. O.P. Gautam, Director General of ICAR, and Vice-Chairman of ICRISAT's Board, pointed out the vital role of the national programs in the transfer of technology from the International Centers.

The Union Minister for Agriculture, Mr. Rao Birendra Singh, agreed to the seminar which took place on 21 May last year. It was attended by the Minister himself, the Secretary for Agriculture and Cooperation, the Director General of ICAR - Dr. Gautam - senior officers of the Union Ministry of Agriculture and of the State Governments of Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Maharashtra and Tamil Nadu, the six states in India where the technology may be applicable. The proceedings of the seminar were published by ICRISAT on behalf of the sponsors.

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[1] Extracted from a presentation of the International Centers Week held at Washington D.C., 9-13 November 1981.

[2] Director General, ICRISAT.

The technology that ICRISAT described at the seminar was a low-input technology based on bullock power within reach of the small farmer in the rainfed semi-arid tropics. It is a technology that can lead the small farmer into the future by being within his reach today: appropriate technology in the positive forward-looking meaning of that phrase. It is based upon the concept of the small watershed as the basic resource management unit. Cooperative and independent research by ICAR and University scientists give results that agree in many respects with those that had been achieved at ICRISAT. The technology is in line with national goals to give greater emphasis to rainfed agriculture so that disparities in income between rainfed and irrigated areas are reduced. It is a technology that will create employment, and is therefore socially relevant.

The components are: cultivating the land immediately after the previous post-rainy-season crop when the soil still contains some moisture and is not too hard, improved drainage through the use of graded beds and furrows, dry seeding of crops before the monsoon rains arrive, the use of improved seeds and moderate amounts of fertilizers, improved placement of seed and fertilizer for better crop stands, and finally, some attention to plant protection, particularly for the legume crop.

The benefits are substantial: average annual profits using the new technology are some six times those using traditional technology. Returns to additional costs average about 250%.

The benefits are not without risk. Absolute variability in profit is increased, although percentage variability is decreased. The needs for human labor increase by 250% or more and the pattern of labor use is changed. More labor is needed in the early months of the cropping year, even in April and May, when traditional farm labor use is minimal. Labor peaks occur at normal times but are much greater. If threshing and harvesting must be done by hand, the labor peaks are extreme, particularly in October and November when the first - that is, the additional crop must be harvested and the second crop planted. There is also a greater need for the use of bullocks. Availability of bullock power represents a serious constraint for the smallest farmers, few of whom own bullocks.

Institutional help is required to: help the smallest farmers obtain access to bullock power, provide for some community drains, and obtain credit for enterpreneurs to purchase the wheeled tool carriers. New marketing strategies may be necessary to cope with increased local supplies of crops. Storage facilities on the farm or in the village may be needed to prevent spoilage and to ensure that whatever is supplied to the market is in reasonable balance with demand.

We know that this technology is not suited to all the deep black Vertisols of the world. Dry seeding is an essential component of the technology. For it to be successful the early rains must be reasonably reliable. As a general rule this can be equated to a rainfall greater than 750 mm per year.

We have not yet estimated accurately the area to which this technology is suited, but it is at least 5 and may be as much as 12 million hecatres. The technology is not ready for adoption on all this vast area of land. Our scientists, the Technology Transfer Committee and the Governing Board believe that the technology is ready for trial in operational research studies and pilot projects. There are weaknesses in the technology that we know about, and some that we will find only through such studies. The policy issues we have pointed out must be resolved before the technology will get very far. What now is the role of ICRISAT - an international agricultural research and training center - in the followup action that must be taken if the potential of this new technology is to be realized?

We see three roles for our Institute: first, we have recognized that even 7 years of trial at ICRISAT through wet years, normal years, and dry years is no guarantee that the technology will work at the village level. We must play a role in on-farm verification. Second, we must develop awareness in government of the potential of this technology and its limitations and provide training for those who will undertake the operational research and pilot projects. Third, we must continue our research in farming systems to find improvements for the weakest components. We have begun our work in all three roles.

For on-farm verification, we chose a village called Taddanpally, 40 km north of ICRISAT. It had the right soils, slopes, and rainfall. The farmers after some initial hesitation agreed to cooperate with us even though it meant substantial changes in their manner of farming and some changes in other aspects of their lives. The farmers are very poor in this village, but they agreed to pay virtually all the costs and do virtually all the work that was needed to test the technology. Where they needed financial help, the State Department of Agriculture assisted them in finding it, either through the banks or through existing government channels. The research agencies - ICRISAT, ICAR, and APAU - agreed only to provide advice and some services, and ICRISAT agreed to compensate the farmers up to the normal level of their traditional yields if the experiment proved to be a failure. And so we went to work. In February of this year, after the traditional intercrop had been harvested, ICRISAT and State engineers surveyed the land and planned the watershed, leaving in place the property boundaries. The farmers did the land smoothing work with their own animals and equipment, but used the ICRISAT tool carrier behind their bullocks for most operations. The animals were rather weak, and because the traditional crop was harvested late, the soils were already quite hard. It did not take long for the farmers to get used to the equipment, but the beds and furrows were not terribly well made - although they were no worse than the first ones we put in at ICRISAT in 1973. In a very rainy year they have performed remarkably well. The costs of reshaping the watershed have worked out surprisingly low.

Although the farmers were willing to install drainage ways on their own land they were not willing to work collectively to install the necessary community drains to connect the watershed to the existing main drain system. In consequence in the very heavy rains in the early part of the year the watershed did not work properly and the lower parts of some fields were flooded. When the farmers saw this and saw how this did not happen at ICRISAT, we were able to persuade them to undertake the construction of the community drains. The State Department of Agriculture, through its existing soil conservation programs, paid for their labor to put the drains in place. Since then, in a year where the rainfall has been 70% above normal, there have been no further problems of waterlogging or drainage.

ICRISAT and the other research agencies recommended what crops would be best, but the farmers made their own choices. In consequence, on this 15 hectare watershed with 14 farmers we have eight different crop combinations including the crops of one farmer who decided to stick to the old ways. With one exception, the crops have done extremely well and far exceeded anything else for miles around. Nor surprisingly, there have been some problems such as Striga weed. Usually crops are grown here in the postrainy season only; the farmers are not used to growing crops during the rainy season. As predicted, threshing - sometimes with unconventional mechanization - and storage are problems, particularly because in this very wet year it has not been possible to dry the grain on the head in the field. And this is only the first crop. The second crop is still to come - in February, March, or April.

The second role of ICRISAT is to create awareness and provide training on the details of the new technology. Our policy level seminar was the first step in creating awareness. Then we held two 2-day workshops for senior officials from the interested states to acquaint them with the technology and how it works. In mid-October 1981 we held two week-long workshops for the middle level officials of the states who will be responsible for guiding and supervising the operational research or pilot studies. In February 1982 we held a 4-6 week training program for the extension officers and subject matter specialists who will have direct responsibility for working with the farmers in implementing the studies.

Taddanpally village provides a training site as well as a place for on-farm verification of the technology. All our visitors go to the village to meet the farmers and to see what has been done.

In addition to our on-farm research at Taddanpally village, we have continued on-farm research at two villages in Maharashtra and one in Andhra Pradesh, where we began baseline studies in 1975. In these villages, after 3 years of working with the farmers to fit new technologies to their conditions, we have reduced our direct assistance to technical advice, but continued to measure the economic and social parameters that we have measured all along. Next year, after the farmers have decided what portions of the introduced technologies they wish to adopt, we will carry out some scientific adoption studies to learn what was adopted and what was not, by whom and for what reasons. Thus we will have come full circle for the first time.

Based upon the experience we have gained in this circular process, we have reexamined critically the concepts and methodologies of ICRISAT farming systems research. We have been assisted in this review by the Program Committee and particularly by two Board Members, Drs. John Dillon and Guy Vallaeys who were members of the TAC-appointed Team that carried out a Stripe Review of Farming Systems in the International Centers in 1977 and 1978. As a result of our Review, we can now state the concepts more clearly and we have reorganized our farming systems program to improve its focus and increase its effectiveness.

The four major subdivisions of farming systems research similar to those proposed by the Stripe Review Team are: baseline studies, component research, research-station operational research, and on-farm operational verification. All subdivisions are necessary, they proceed simultaneously with much feedback and interaction. The priorities among them change with time and circumstances.

Farming systems research begins and ends on the farm. It is multidisciplinary, involving scientists, farmers, government, and private industry. It emphasizes problem-oriented research. Its methods must be scientific, but its results - at least in rainfed agriculture - must be expressed stochastically, that is, in terms of probabilities.

Baseline studies, which include diagnostic studies on crop management and production, must take cognizance of all aspects of the system. Livestock production and forestry must be included where they are relevant.

Component research, whether basic or applied, must be problem-oriented and as much as possible 'in context' with the system under study. Sound baseline studies reduce the complexity of that context and allow component research to achieve greater rigor, depth, and sophistication.

Research station operational research is a necessary component, both as a prior step to on-farm research, and to obtain accurate data on time-dependent variabilities.

In on-farm research we test or verify improved technology, make adoption studies, test the validity of baseline studies, and provide data with demonstration value.

Modeling is an important component of farming systems research, but the useful models are those that are susceptible to experimental verification.

Farming systems research is location-specific. The more complex the system under study, the more specific it becomes. The constraints are physical, biological, economic, and social. Resource constraints are the most intractable. They define the limits of improvement that are possible. Certain minimum sets of data must be obtained on-station and on-farm to reduce physical location-specificity and to enable technology transfer to occur. Social and economic constraints are less intractable than resource constraints and are more time-dependent.

The successful operation of farming systems research programs places great demands upon the scientists. Coordination must be frequent and be undertaken by the people directly involved. Team work is essential; the team changes and team leadership changes with the task. Team leadership does not respect seniority. A high standard of professionalism is required, which in turn requires that personal, professional goals must be realizable within the system and the team. The organizational structure for farming systems research must be flexible, and no one program can be given total responsibility for an institute's farming systems research.

We are confident that with our new understanding we have entered a new, more effective, and more exciting phase in farming systems research. We hope that you will be interested in monitoring our progress and will come to see our work in the years ahead.

Sastry/29482