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Soil Mapping and Advisory Services

Botswana

PHYSICAL PROPERTIES, MOISTURE REGIME AND CROP PRODUCTION A CASE STUDY ON A LUVISOL IN SEBELE

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PHYSICAL PROPERTIES, MOISTURE REGIME AND CROP PRODUCTION
A CASE STUDY ON A LUVISOL IN SEBELE

By

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The conclusion given in this report are those considered appropriate at the time of its preparation.
They may be modified in the light of further knowledge gained at subsequent stages of this project.

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1. INTRODUCTION

The physical properties of a Luvisol in the Agricultural Research Station in Sebele was studied in detail for use in interpreting research trials in the Station. The soil physical properties measured are (a) particle size distribution (b) bulk density (c) Infiltration characteristics (d) soil moisture retention properties (e) structural stability and (f) unsaturated hydraulic conductivity. The measured soil physical properties were either directly interpreted or were used to derive other properties which are important in agriculture. In addition, moisture regime of selected sites in the Luvisols were monitored regularly to study the weekly variation of profile moisture contents in response to rainfall. The data was used to develop a methodology to predict bare soil evaporation and soil moisture storage in the Luvisol under natural rainfall condition. The model was validated and used with 40 years rainfall records for Gaborone to identify planting opportunities based on soil moisture storage. The FAO model for yield response to moisture was then used with the estimated soil moisture storage at planting time to predict potential yields in order to assess long range effects of soil moisture stress on sorghum yields in these Luvisols.

The Luvisols in the hardveld regions in Botswana vary in their properties depending on the nature of their parent material and the topographic position in which they occur. The Luvisols in the Agricultural Research Station in Sebele are derived from acid igneous and metamorphic rocks. Most of these soils can be broadly described as moderately deep coarse sandy loams to sandy clay loams. The soils on the upper positions of the gently undulating topography are well drained and gradually becomes imperfectly drained in the lower positions. These Luvisols are classified as Ferric Luvisol, Chromic Luvisol or Haplic Lixisol according to the differences in the colour and cation exchange capacities. The texture and the structural properties of these soils vary only within a narrow range. Consequently the physical properties are very similar for the Luvisols in the Agricultural Research Station. Description of the typical Ferric Luvisol which was studied is given in the annex. Individual horizons of the profile that were similar in texture, structure and compactness were grouped together for the measurement of physical properties. Soil samples for physical analysis were taken from the largest of these grouped horizons.

The moisture regime of these Luvisols can vary according to whether they are located in water shedding or receiving positions in the landscape. The moisture content of a soil profile at any instant of time is the soil moisture storage resulting from the moisture balance between rainfall, run-off or accumulation, evaporation and deep drainage losses. In addition to climate and topography, soil physical properties play a significant role in determining the moisture regime of the soil profile at a site.

The moisture regime of a bare soil can be used to identify periods of adequate soil moisture storage during the growing season for planting and subsequent crop growth.

2. SOIL PHYSICAL PROPERTIES

2.1. Particle size distribution

Particle size analysis to determine the proportions of sand, silt and clay was carried out by a combination of sedimentation and seiving procedures (Table 1). In the surface horizons, the coarse and the medium sand predominate and decrease with depth. The silt content is very low throughout the profile ranging from 2 to 3 percent only. The clay content increases with depth from about 15 percent to a maximum of 27 percent. The proportion of fine sand and silt remains constant throughout the profile. However, surface horizons with lower clay content are common and the textures generally change from loamy sand to sandy loam to sandy clay loam with increase in depth.

The very low silt content with clay content in the range of 10 - 30 percent appears to be the typical particle size distribution that causes surface crusting and hard setting properties in soils. This indeed is a character of the Luvisols. However, higher organic matter content in the soil does improve the structural properties of these soils.

Table 1: Particle size distribution - Ferric Luvisol, Sebele

Depth cm	Particle size (weight%)							
	vcS	cS	mS	fS	vfS	cSi	fSi	clay
0 -33	7	27	19	18	9	2	2	17
33-69	9	23	21	18	8	2	2	23
69-139	6	12	17	21	13	3	2	26

vcS - Very coarse sand
cS - coarse sand
mS - medium sand
fS - fine sand
vfS - very fine sand
cSi - coarse silt
fSi - fine silt

2.2. Bulk density and total porosity

The bulk densities of the different horizons were determined by obtaining undisturbed cylindrical soil samples of known volume and dividing the mass of oven dry soil by the field volume. Table 2 gives the average bulk densities of the grouped horizons. Except for the surface horizon, the bulk densities are uniform with depth. The higher bulk density of the surface horizon is presumably due to the coarse sand fraction and the hard setting nature of these soils. In the absence of organic matter the bulk densities of the Luvisols vary between 1.55 and 1.65gm per cc.

Assuming that the average value for particle density is 2.65gm per cc, the total porosities of the three horizons are 37,41 and 41 percent. These values for the total porosities are representative for this soil textural class.

2.3. Infiltration characteristics

The infiltration rate is the rate of water entry into the soil at the surface. The infiltration characteristics of a soil are dependent on texture, structure and the initial moisture content. The double ring infiltration method was used to measure the infiltration characteristics. A fundamental relationship between cumulative infiltration F and elapsed time t is commonly used to describe soil infiltration namely.

$$F = at^n$$

Where a, and n are constants.
The equation when transformed into logarithmic form becomes

$$\text{Log } F = \text{Log } a + n \text{ Log } t$$

The plot of log f versus log t is a straight line with the intercept in the "y" axis equal to log a and gradient equal to n. The infiltration always decrease with time to a constant value referred to the "basic infiltration" rate. The basic infiltration rate is characteristic for the soil. The magnitude of "a" gives the initial infiltration rate and "n" gives its rate of decrease.

Table 3 gives the basic rate, "a" and the "n" values for 5 infiltration tests carried out in the Luvisol in Sebele. The results show that the infiltration are quite variable. Test Nos. 1,2 and 3 were carried out on ploughed soils, thus giving higher infiltration rates. The magnitudes and the variation of the basic infiltration rates of these 3 tests are typical for sandy soils and can be classified as high to very high. Test No. 4 was

Table 2: Moisture retention data and bulk densities for the horizons of Ferric Luvisol - Sebele

Depth cm	Bulk density g/cc	Water content (Weight%) for different tensions (bar)							
		0.03	0.05	0.1	0.03	1.0	3.0	5.0	15.0
0 -33	1.66	13.43	12.26	9.27	7.26	5.90	4.30	4.10	3.90
33-69	1.55	15.02	13.80	10.21	7.93	6.80	5.60	6.20	6.00
69-138	1.55	17.66	15.51	13.43	11.18	8.90	7.40	6.90	6.40

Table 3. Infiltration characteristics of Ferric Luvisol - Sebele

Test. No.	Basic rates cm/hr	"a" value	"n" value
1	13.0	0.72	0.80
2	6.4	0.78	0.69
3	4.4	0.37	0.74
4	0.7	0.33	0.53
5	30.2	0.55	0.98

"a" and "n" values are constants in equation

$$F = at^{n}$$

F = cumulative evaporation, t = elapsed time

carried out on an unploughed site which had been cultivated earlier. The soil at this site was hard and compact and this property is reflected in the low infiltration rates. Test No.5 was carried out on an adjoining site which was still under grass and bush cover. The soil at this site was well structured with high organic matter and faunal activity. Consequently, the infiltration rate was very high to excessive due to the macro-pores present in the soil. The range of infiltration rates is typical for these soils depending on the history of land use.

2.4. Soil moisture characteristics

The soil moisture characteristic curve relates soil water content to soil water potential or soil water tension. It is the moisture content of the soil retained in the soil pores against applied pressure or suction. The logarithm of the water suction measured in centimeters is commonly referred to as pF. The moisture characteristics for the three grouped horizons of the Luvisol was measured by the pressure plate apparatus and sand table. Table 2 and Figure 1 shows the moisture retention data. Generally as the tension is increased from zero, the moisture content of the soil decrease due to the draining of the large pores initially and progressively followed by the smaller pores. The amount of moisture released for each increment of tension also gives the proportion of pores within the given size range corresponding to the tensions.

The moisture retention curves in Figure 1 indicate that the three horizons are similar in their moisture release characteristics except that as the depth increase the soils retain slightly more water at any particular tension than the soil horizons above it. Between zero and pF 2.0 tension, i.e between saturation and field capacity, almost 50 percent of pores are drained. This implies that 50 percent of the pores are large and freely draining, as could be expected for soils with high proportion of coarse sand. The increased moisture retention of the lower horizon at tensions greater than pF 2.0 indicate the presence of higher proportion of micro-pore in the lower horizon. This is generally the case when the clay content increase. The parallel nature of the moisture retention curves between pF 2.0 and 4.5 also shows that the pore size distribution of the soils in the three horizons are similar in this range of tension.

2.4.1 Moisture availability and aeration:

The amount of soil moisture available for plant growth is considered to be the moisture held in the range from field capacity to permanent wilting point. The field capacity is defined as the water content of soil when free drainage of an initially saturated soil has decreased to negligible rate. Permanent

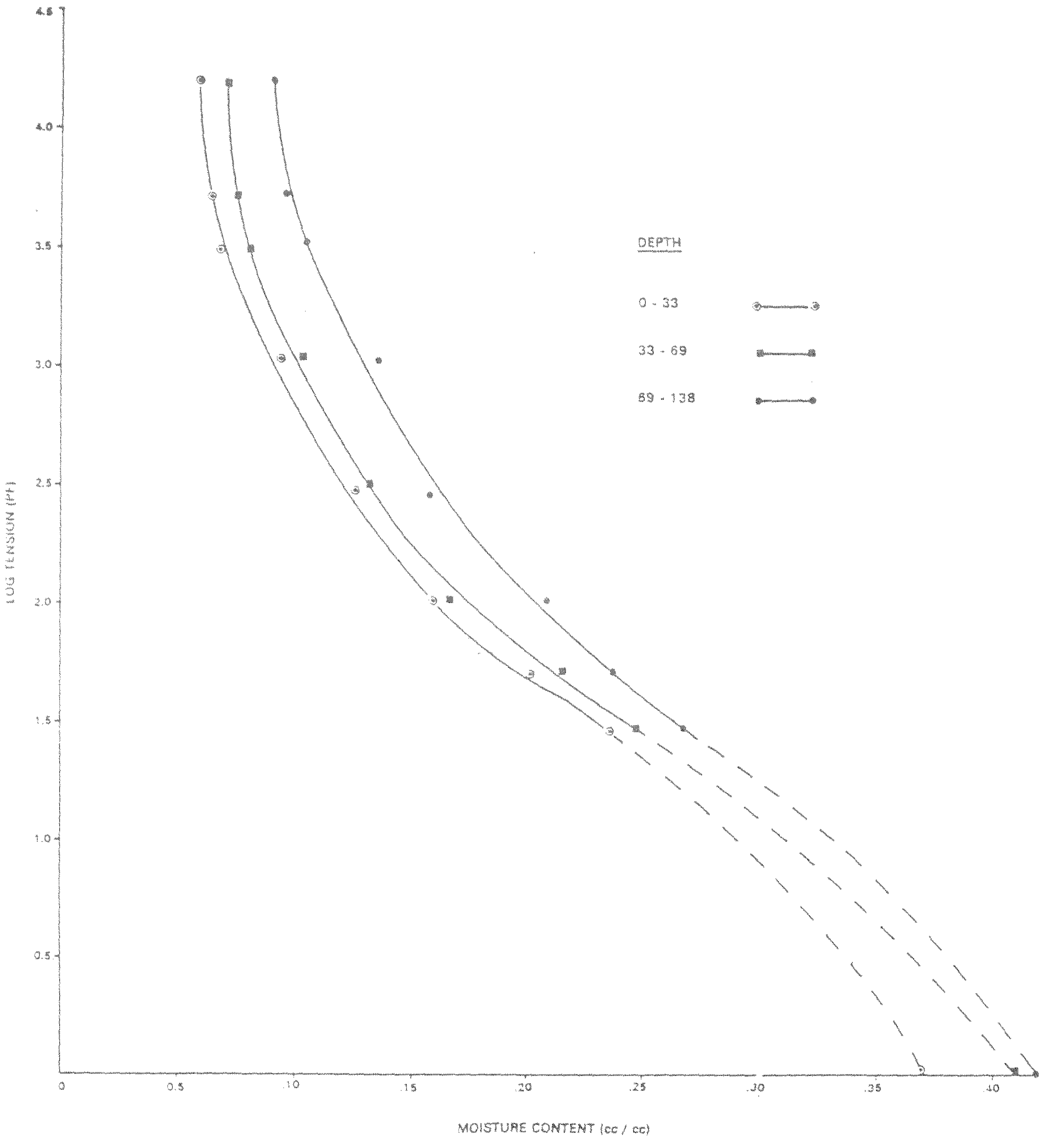


FIGURE 1 : MOISTURE CHARACTERISTICS - FERRIC LUVISOL (SEBELE, BOTSWANA)

wilting point is defined as the moisture content of soil at which plants wilt permanently due to soil moisture deficiency. In a field experiment, the change of moisture content with time for the freely draining saturated Luvisol profile was measured. Figure 2 shows the plot of moisture content versus time for three depths. In general the rate of decrease of moisture content becomes negligible after 60 hours. The volumetric moisture content of the three horizons after 60 hours of drainage are 15.0, 16.0 and 19.8 percent. These moisture contents correspond to a tension of pF 2.0 in the moisture retention curve. Thus, for these lighter textured soils, the field capacity can be approximated to the moisture content at pF 2.0. For all soils, it has been shown that wilting point correspond to moisture content at pF 4.2. Based on the results from moisture retention measurements, the moisture availability for plant growth are shown in Table 4.

Table 4. Average available moisture for the different horizons of Ferric Luvisol - Sebele

Horizon depth cm	Field Capacity cc/cc	Wilting point cc/cc	Total.av.moist cc/cc	mm/m
0 - 33	.1538	.0647	.0891	89.1
33- 69	.1582	.0924	.0658	65.8
69-138	.2068	.0985	.1083	108.3

Average available moisture = 92mm/m

The aeration capacity of a soil is defined as the volume percent of air space or air porosity at field capacity. The aeration capacity for the three horizons of the Luvisol are 21.0, 25.0 and 20.3 percent by volume. Generally at least 10 percent air porosity is essential for satisfactory plant growth. The air porosities of the Luvisols are well above this threshold value and hence provide adequate aeration for plant growth.

2.5. Structural stability

The degree to which the soil aggregates withstand the disintergrating effect of water and mechanical agitation is referred to as structural stability. The structural stability indices were measured as a ratio of the volume of easily draining large pores after slow wetting under suction and quick wetting by flooding. Under slow wetting, structural aggregates do not collapse while under fast wetting they collapse and slake according to their degree of stability. Soil samples in the size range between 1 and

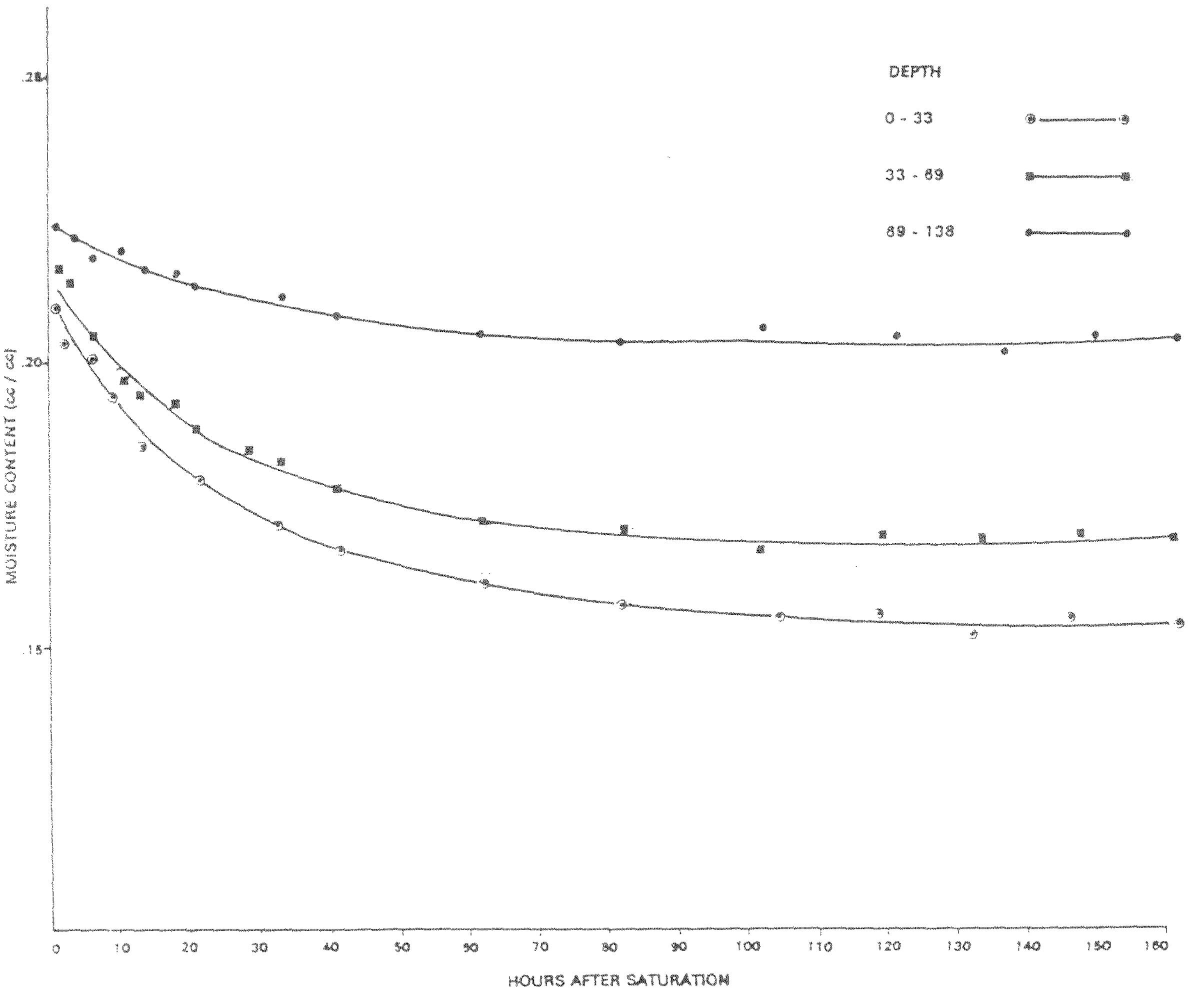


FIGURE 2 : FREE DRAINAGE OF COVERED SATURATED PROFILE OF FERRIC LUVISOL (SEBELE, BOTSWANA)

2 mm are used for the measurement. The structural stability indices vary between 1 and 0 corresponding to completely stable and completely unstable aggregates respectively. In general, structural stability index is measured only on surface soils because of their significant influence on surface sealing, erosion and run-off during rainfall.

The structural stability index measured by the above method has to be interpretd in relation to the proportion of single grains which do not undergo disintergration on fast wetting. The single grains tend to increase the value for the structural stability index than what it should be for the real structural aggregates. The structural stability index of the Luvisol is 0.49 and the sand fraction itself is about 70 percent. Therefore the structural stability index of the soil aggregates will be much lower than 0.49 indicating very poor stability. Thus these soils will tend to form surface crusts and induce run-off and erosion under rainfall.

2.6. Hydraulic conductivity

No attempt was made to measure saturated hydraulic conductivity as soil profile saturation is only an occasional occurence under semi-arid conditions. However, if required, the saturated hydraulic conductivity can be approximated to the basic infiltration rates.

The unsaturated hydraulic conductivity of the Luvisol was measured by the field water balance technique. A field plot 2m x 2m was flooded so that the entire profile was saturated. Immediately after saturation, the soil surface was covered with plastic sheets and loose dry soil thrown over it to prevent any evaporation or infiltration. While the soil profile was draining under gravity, soil moisture content was measured by neutron moisture probe at 15cm depth increments from 0 to 120cm depth. The measurements were made at 4 hour intervals at the beginning and reduced to 12 hour intervals after 3 days. When drainage rate was very low, measurements were made at 5-7 day intervals. In calculating the hydraulic conductivity, the hydraulic gradient was assumed to be unity as it is usually the case during field drainage.

The results indicate that the soil profile can be grouped into three layers namely 0-45cm, 45-75cm and 75-120cm according to the similarity in the hydraulic conductivities. Figure 3 show the variation in hydraulic conductivities with moisture content for these depth intervals. At high moisture content between 0.20 and 0.22 cc per cc, the hydraulic conductivities for all depths are similar, varying between 0.1 and 1cm per hr. As moisture content decreases, the drop in hydraulic conductivity is higher for the lower depths which have higher clay contents. Conversely, for any

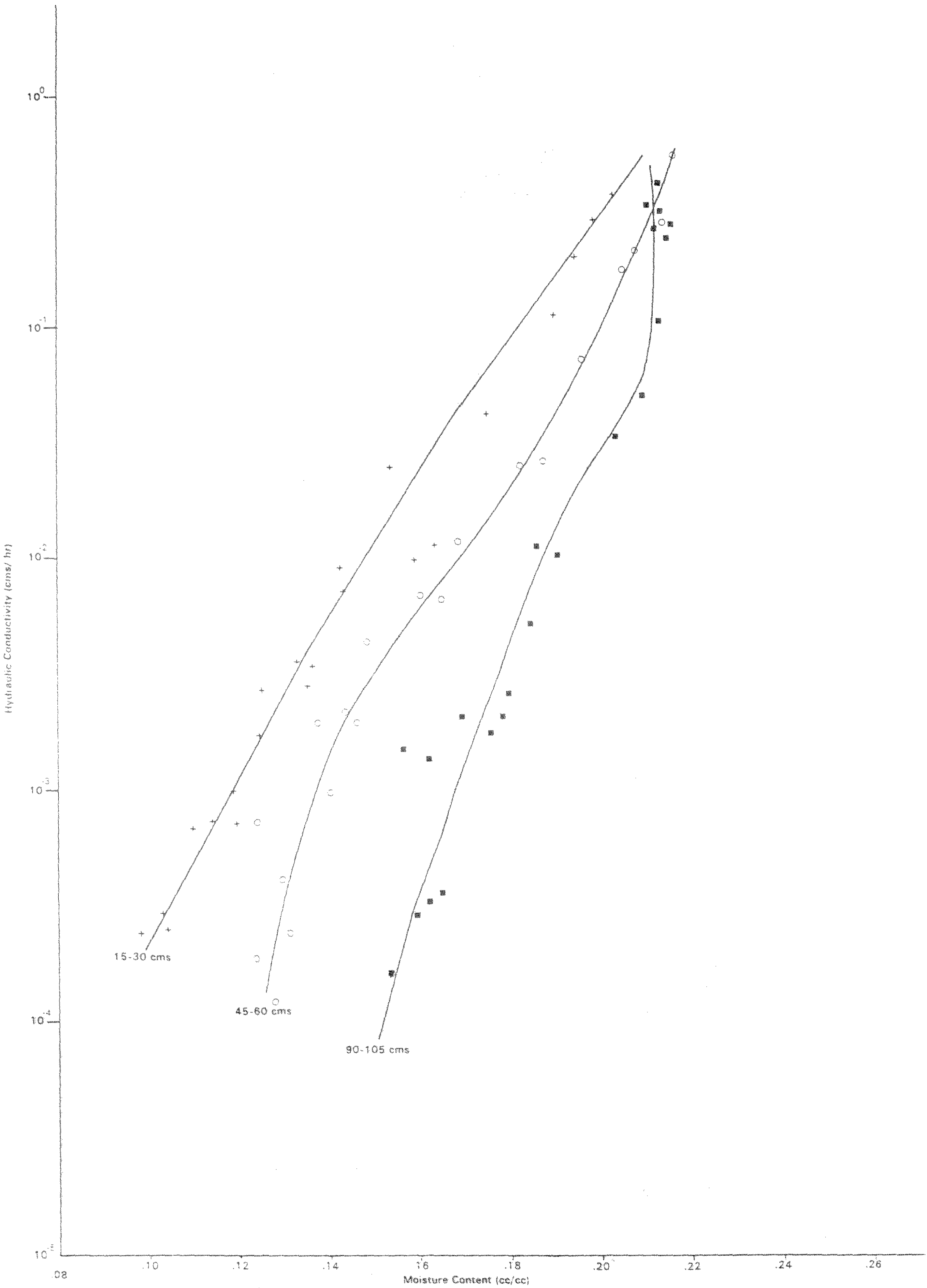


FIGURE 3 : UNSATURATED HYDRAULIC CONDUCTIVITY - FERRIC LUVISOLS (SEBELE, BOTSWANA)

value of the hydraulic conductivity, the lower horizons have higher moisture content than the upper ones. In general, for all horizons, the hydraulic conductivities range from 1cm/hr to $1x10^{-4}$cm/hr. However for this change in the hydraulic conductivity, the moisture content of the upper layer decrease from 0.21cc/cc to 0.08cc/cc where as the change in the lower horizon is from 0.21 cc/cc to only 0.15 cc/cc. This behaviour presumably is due to the clays contributing to an increase only in the non-conducting and non-draining small hygroscopic pores. These micro pores increase the moisture content at any tension without affecting the hydraulic conductivities. The pores which contribute to the movement of water in the soil are similar in their size distribution for the three horizons as seen in the moisture characteristic curves.

3. SOIL MOISTURE REGIME

The variation of soil moisture content of four Ferric Luvisol profiles in response to rainfall was monitored weekly for two and half years commencing from December 1987. Three sites were located in a toposequence of the very gently undulating topography of a field in the Agricultural Research Station in Sebele. One site was selected on the upper position of a slope close to a rainfall recording meteorological station, also in the Research Station. Aluminium access tubes for measuring soil moisture by neutron moisture probe were installed in these sites. A circular area of 2m radius around each tube was clean weeded and kept bare throughout. The changes in soil moisture recorded were mainly due to evaporation from the bare soil. The sites and the access tubes installed along the toposequence from the upper to the lower position were numbered 1,2 and 3 respectively while the site and the access tube near the meterological station was numbered 4. The soil moisture was measured at 15cm depth increments from 0-105cm. The soil profile of access tube No. 3 was shallow with an impermeable petro-calcic layer at 75cm depth. Consequently run-off water from upper slopes caused perched water table during rains, thereby making soil moisture measurements impossible. Results of tube No. 3 are not interpreted for to this reason.

Figures 4a,4b,5a,5b,6a,6b, show the variation of moisture content in the different 15cm depth layers for the period of measurement. The variation of the total moisture in the profile and the rainfall amounts are also included in the figures. The figures themselves are self explanatory. However, some observations are given below.

In general, the changes in soil moisture content in the different soil depths, in response to rainfall, follow the same trend for all the sites. The amplitude of the fluctuations in the moisture content is the highest for the surface layer and progressively decreases for lower depths. This is the expected pattern in the changes in soil moisture as the wetting and the drying process is highest in the surface layer. Except in cases of heavy rain spells, the wetting and drying in confined to the surface layer up to 45 and 60cm depth. Small intermittant rains do not register any increase in moisture, if they occur in the intervening periods between measurements. These small rains tend to evaporate away before the next measurements are taken. During the growing season there are always rains large enough to wet the whole profile. The rate of decrease in the moisture content due to evaporation is lowest for the deeper layers and becomes negligible when the surface layers are very dry. After the rainy season, the surface soil layer becomes almost air dry by the end of June and the layers below lose moisture very slowly over the winter months. However, the overall moisture loss during the entire winter months is large enough to deplete the entire reserve of available moisture in the profile. Although the trends in the changes in moisture contents is similar for all sites, the actual moisture contents is site specific depending on the particular profile characteristics.

The soil profile in which access tube No. 1 was located was deep without any impeding layer within 150cm. Consequently this is a freely draining profile. The full range of variations in the moisture contents recorded would have been due to the combined effect of rainfall, evaporation and free drainage. The profile moisture in the 0 - 105cm varied from a maximum of 110mm to a minimum of 70mm.

In the soil profile of access tube No. 2, there was a heavier textured, low permeable horizon in the 30 - 45cm depth. The profile also had a impermeable petro-calcic horizon at a depth of 120cm. In addition, as the location was in the mid -position of the slope, there was accumulation of run-off from the upper positions. As a result of all these factors, the moisture content at all the depths were higher than site No. 1 during most of the rainy period. However, during prolonged dry spells and during winter months, the moisture contents of 0 - 15cm and 15 -30cm depths were comparable to those of site No. 1. The total profile moisture content in 0 - 105cm depth varied from a maximum of 200mm to a minimum of 125mm. The moisture contents of the lower layers were high due to the accumulation of moisture at the petro-calcic horizon. Thus, the overall moisture content of the profile was high throughout.

The soil profile in site 4 was very similar to site 1 except that it had a petro-calcic horizon at 120cm depth. The accumulation of internally drained moisture at this impermeable horizon caused high moisture contents in the three layers below 60cm. The moisture contents and their variation in the layers above 60cm depth were very similar to site 1. Due to the high moisture contents in the lower layers, the total profile moisture was higher than site 1, ranging from a maximum of 175mm to a minimum of 110mm in the 0-105cm depth.

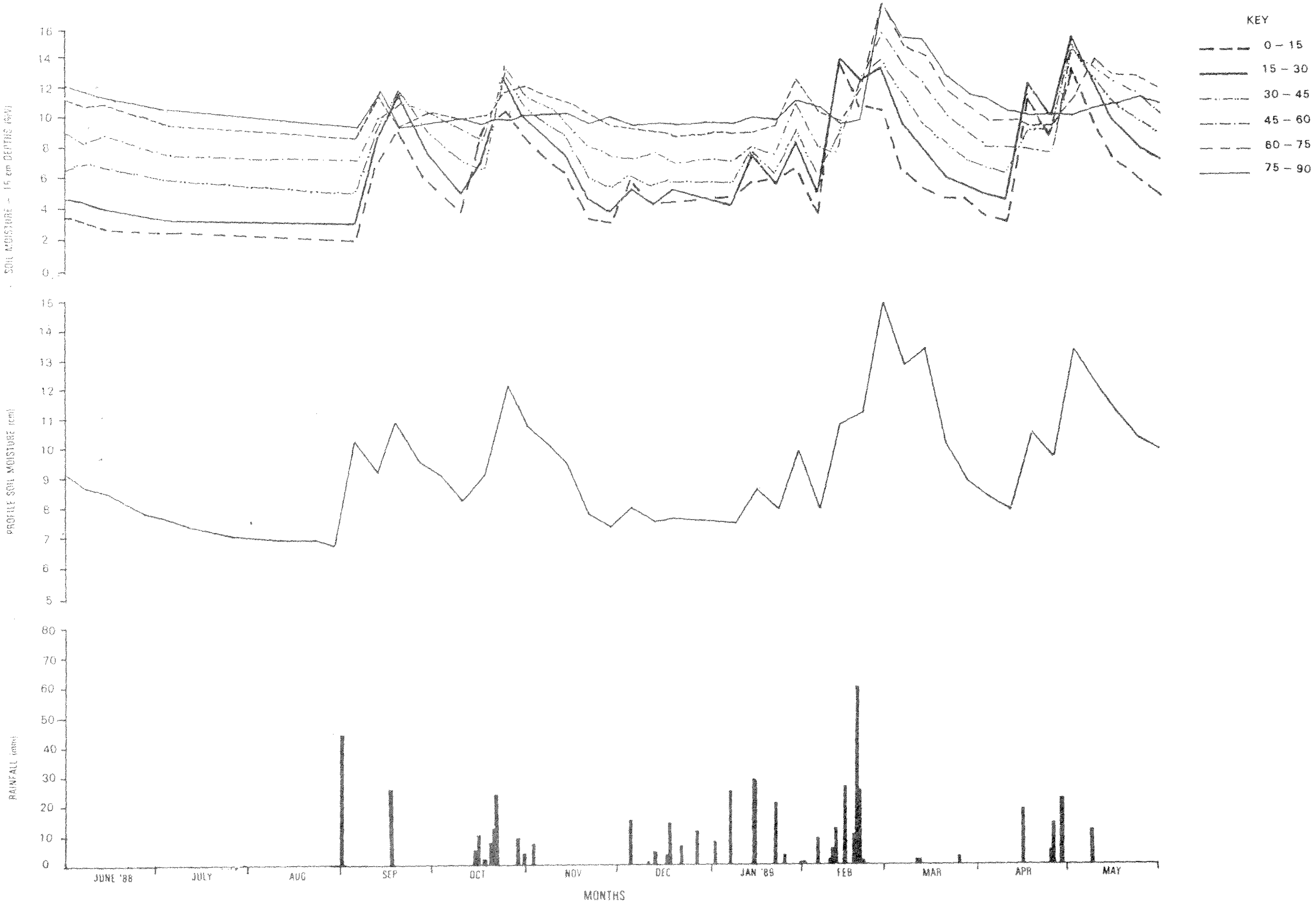


Fig. 4a: Rainfall, soil moisture for profile and 15 cm depth increments for period 1988/ 89 - Site 1 (Sebele)

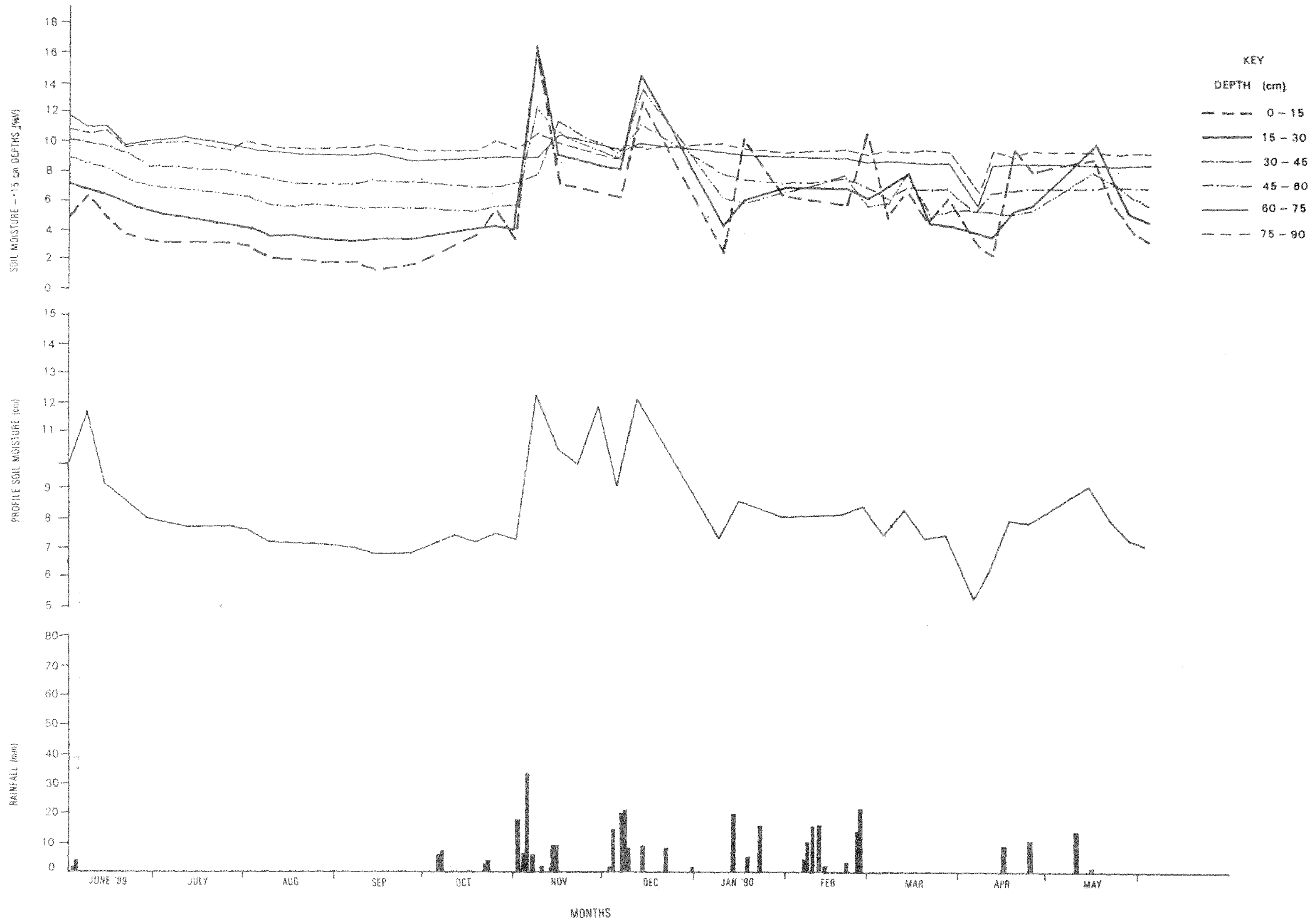


Fig. 4b: Rainfall, soil moisture for profile and 15 cm increments for period 1989/ 90 - Site 1 (Sebele)

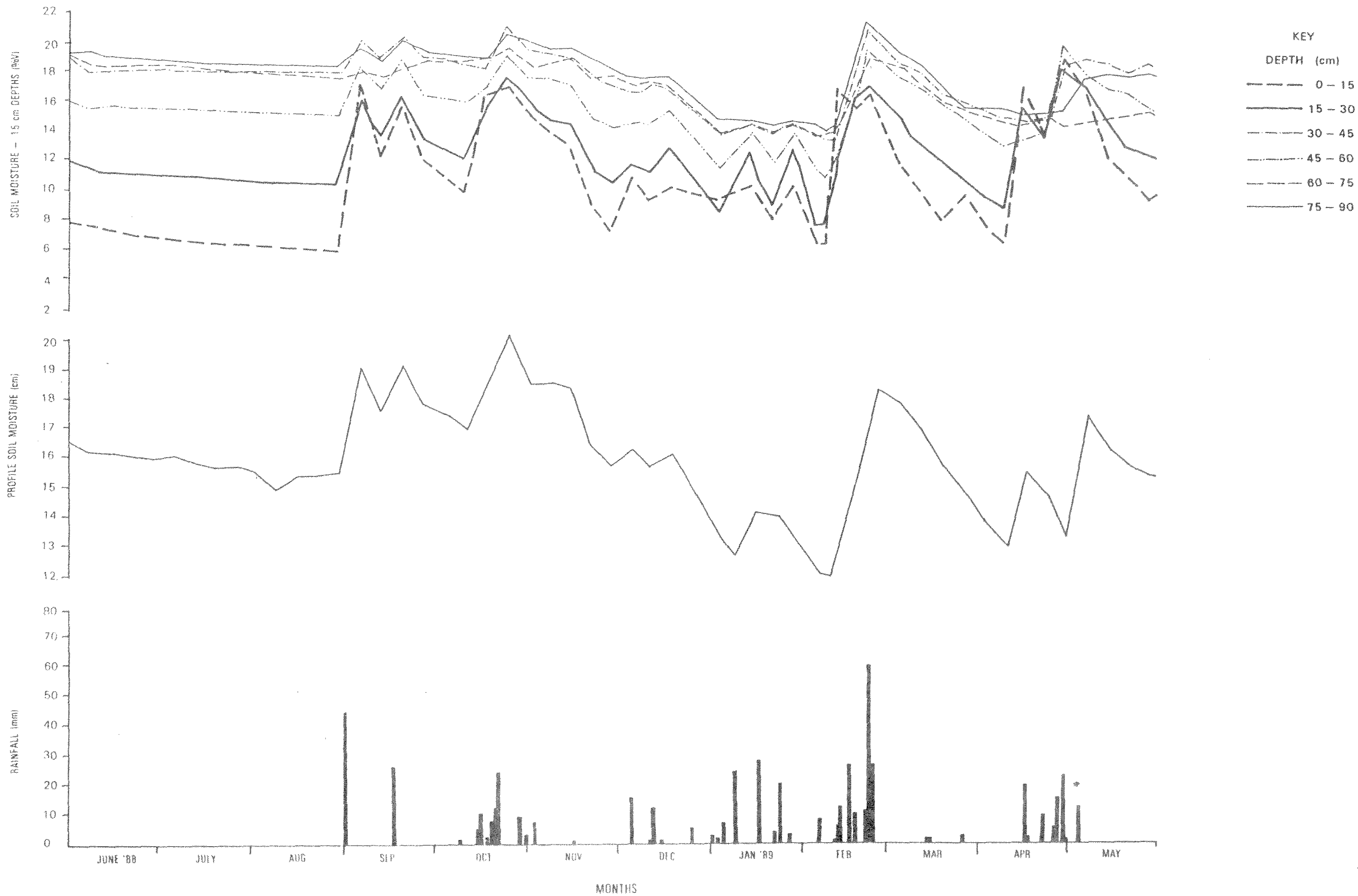


Fig. 5a: Rainfall, soil moisture for profile and 15 cm depth increments for period 1988/ 89 - Site 2 (Sebele)

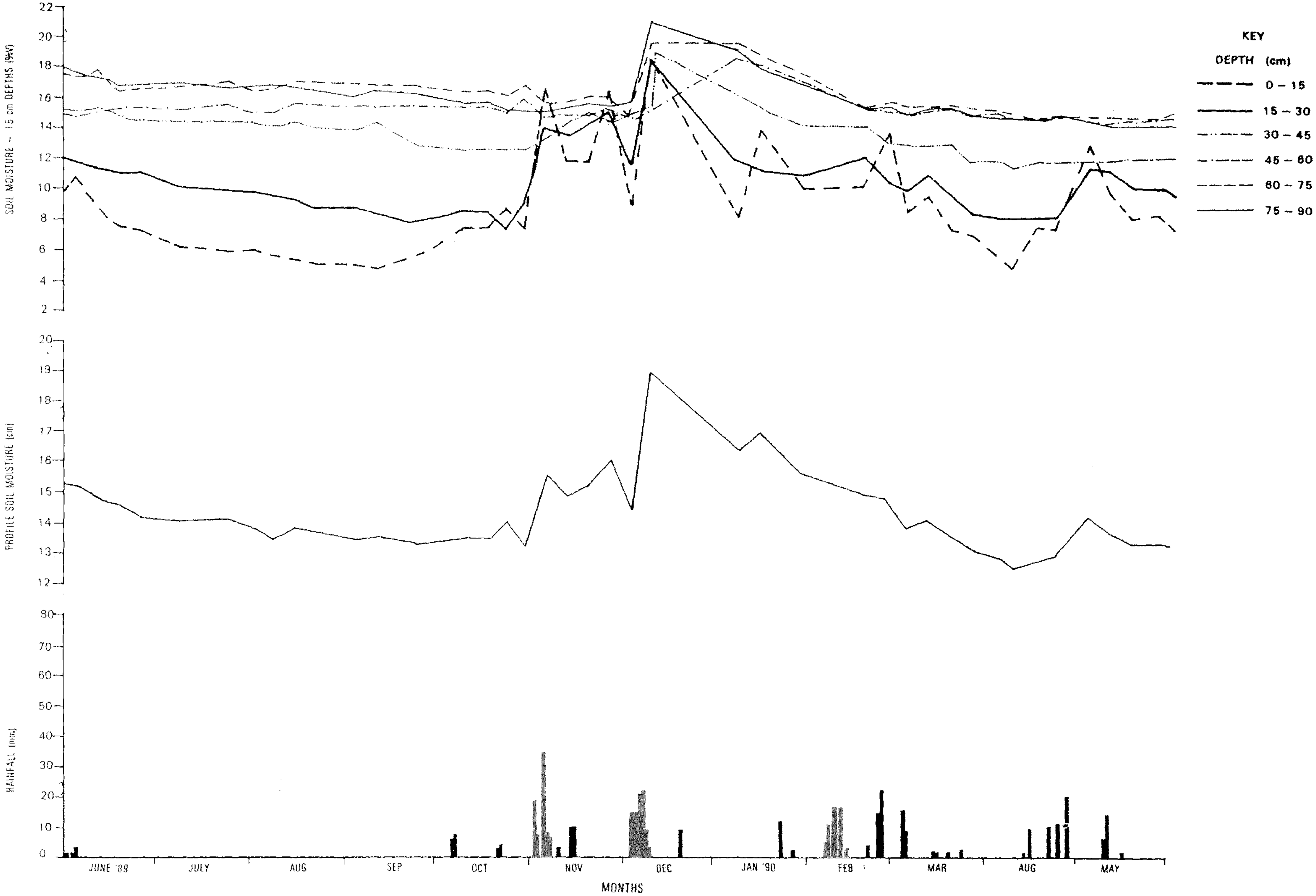


Fig. 5b: Rainfall, soil moisture for profile and 15 cm depth increments for period 1989/ 90 - Site 2 (Sebele)

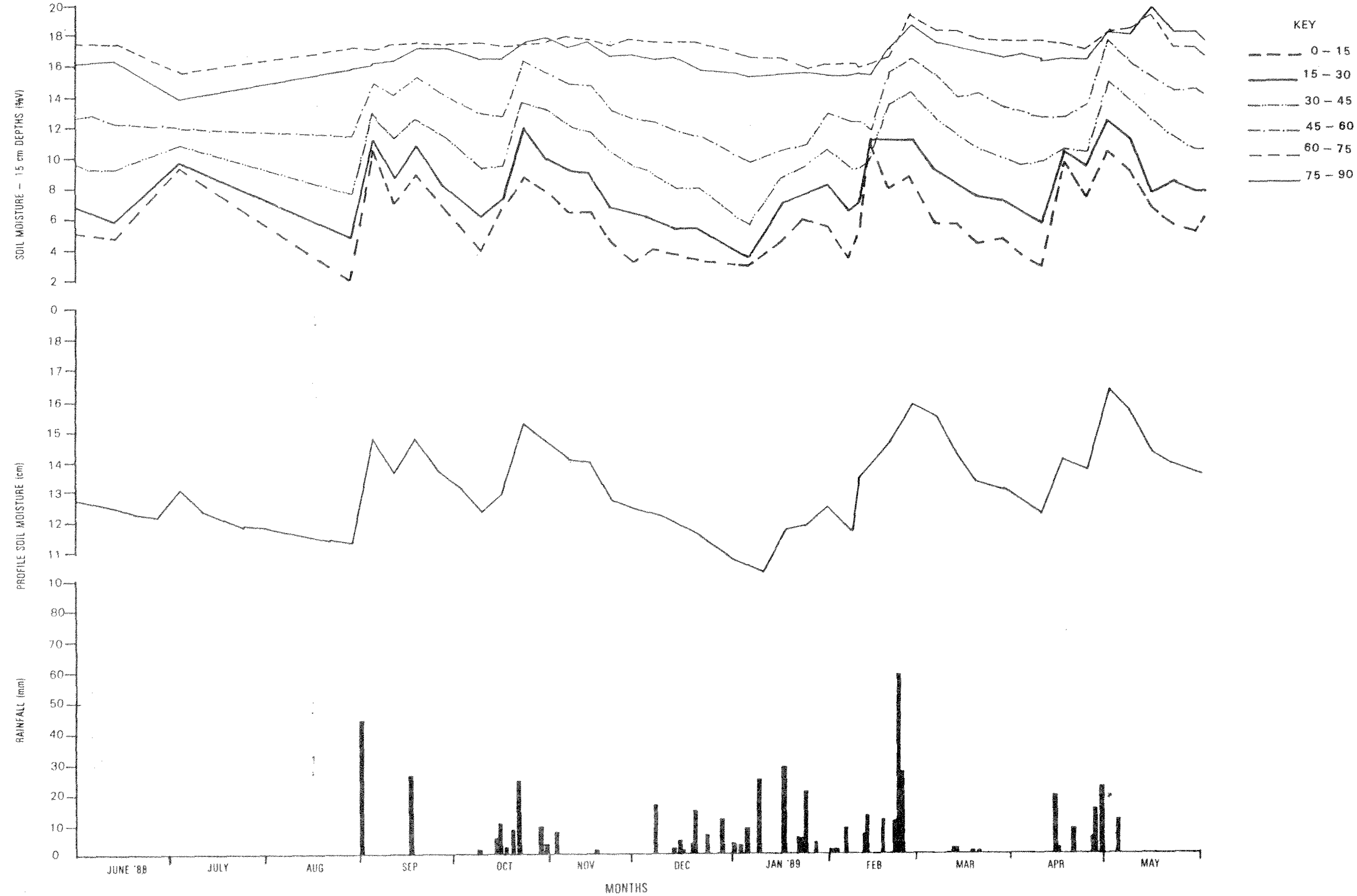


Fig. 6a: Rainfall, soil moisture for profile and 15 cm increments for period 1988/ 89 - Site 4 (Sebele)

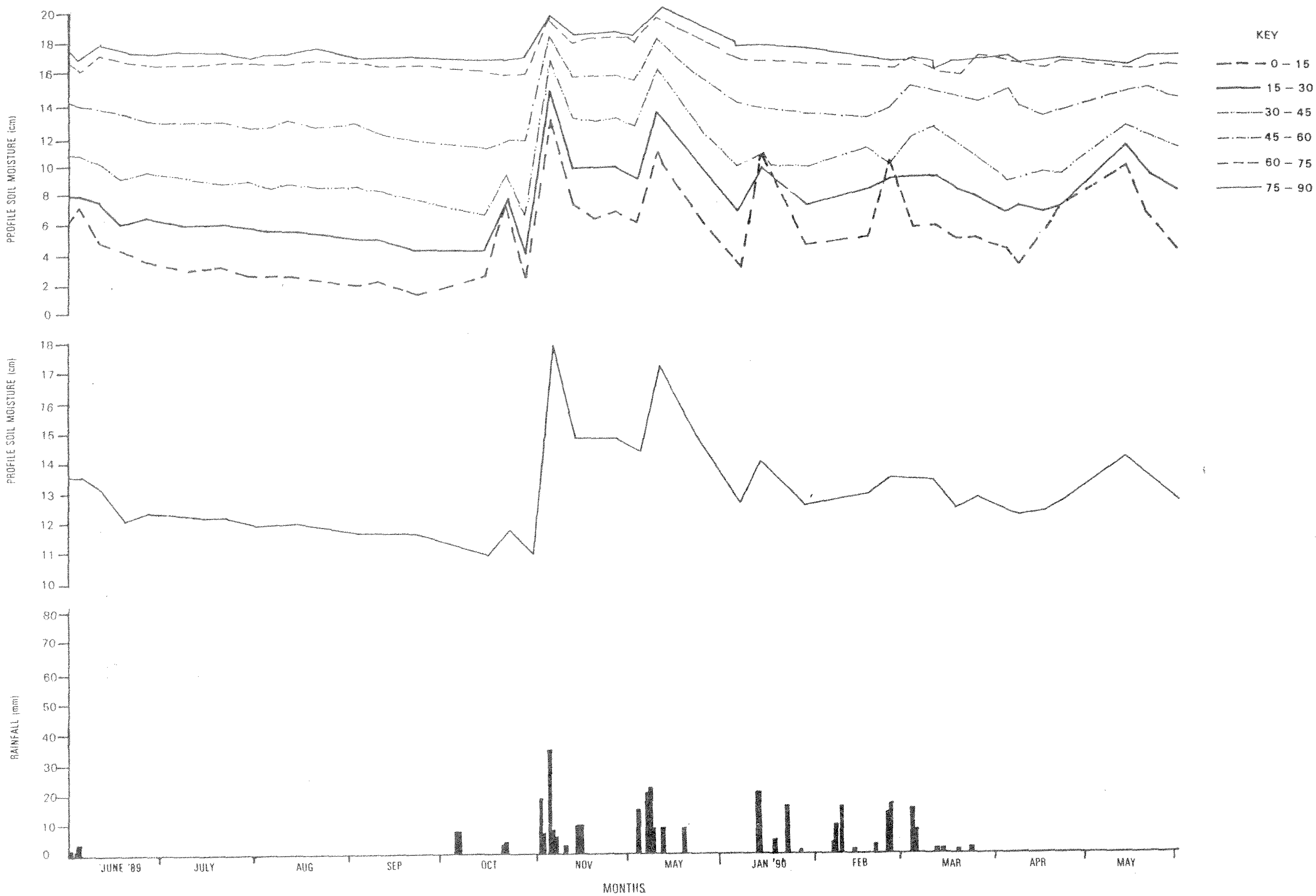


Fig. 6b: Rainfall, soil moisture for profile and 15 cm increments for period 1989/ 90 - Site 4 (Sebele)

4. SOIL MOISTURE BALANCE AND CROP PRODUCTION

In semi arid regions like Botswana, yields of rainfed crops are poor with wide yearly variations. This is often attributed to moisture stress caused by the low and highly variable rainfall. Little attempt has been made to quantify the relative decrease in yields due to the moisture stress alone as compared to the maximum yield that is possible under good management and without any limitations in water supply. Under actual rainfall conditions the potential yield depends on the planting date and the water supply during the subsequent growing period. To predict such potential yield it is necessary to study the moisture balance of bare soil before planting to obtain optimal planting opportunities. Moisture balance study of a cropped soil for each planting opportunity can then be used to calculate potential yields taking into account the yield reduction due to moisture stress. Thus, there is a need for a methodology to have a reliable estimate of soil moisture storage in a bare soil and a methodology to predict yields of crops under actual rainfall.

Reliable assessment of yield reduction due to moisture stress is necessary for developing water management strategies in rainfed agriculture. The first part of this chapter presents a practical approach to predict bare soil evaporation based on water flow theory using easily measurable soil physical parameters as inputs. The methodology also incorporates evaporation processes that are observed in laboratory experiments simulating natural rainfall events wetting bare soil. The model was used for a Ferric Luvisol with forty years of rainfall record for Gaborone to predict evaporation from bare soil and soil moisture storage for ten-day periods. The model predictions agreed well with actual measured values.

In the second part, FAO methodology (FAO,1979) for yield response to water was used to predict rainfed sorghum yields for the forty year period. Planting opportunities in each year were identified from the amount of soil moisture storage as determined from the earlier model. Potential sorghum yields were then estimated for the different planting opportunities that occurred during the growing season of each year. Based on the results, water management and cultivation strategies are discussed.

4.1 Evaporation from bare soil

The drying of bare soil is observed to occur in three recognizable stages. In the first stage, the soil is wet and water moves to the soil surface to match the evaporation potential of the atmosphere. The evaporation rate at this stage is therefore controlled by atmospheric conditions. The second stage begins when the moisture content of the surface soil layers decreases to a point when water cannot move to the surface fast enough to meet the evaporative demand of the atmosphere. The evaporation rate then falls progressively below the potential rate reflecting with the decreasing ability of the drying profile to transmit soil water. Thus, the onset of the second stage and the subsequent evaporation rates are controlled by the hydraulic properties of the soil. The third stage is established when the surface layer becomes so desiccated that the evaporation takes place at a constant slow rate by vapor diffusion. These three stages of evaporation have been demonstrated experimentally in laboratory soil columns (Fisher,1923) and in field experiments (Idso, et al 1974).

Under natural conditions, evaporation from bare soil is a complex, non-isothermal process involving flow of water and heat. However, the isothermal model has been shown to provide a reliable approximation for evaporation especially for longer periods of several days (Philip,1957). Many models which have been developed require inputs which are not readily available or are not easily measurable. Some models use functional relationships between soil and climatic variables developed through statistical analysis. Application of such models will presumably be limited to locations very similar to the site for which the model was developed. The bare soil evaporation models of Black et. al. (1969), Ritchie (1972), Tanner and Jury (1976) and Gardner (1974) use semi-empirical relationships based on water flow theory and other verified evaporation processes applicable to any soil. These models require easily measurable soil parameters but their applicability is limited to conditions assumed for the solution of the soil water flow equation. The model presented in this paper uses concepts from the latter models but is modified to be of general applicability to any soil.

4.1.1 Evaporation stage 1: Evaporation in the first stage persists until the cumulative evaporation from a wet soil profile at field capacity reaches a fixed amount U (Gardner and Gardner,1969; Ritchie, 1972). The amount U, and the depth of moisture depletion LC during this stage depends on the hydraulic properties of the soil. Both U and LC can be easily established for any given soil by measuring cumulative evaporation from a wet profile in a single drying cycle. Field measurements of soil moisture over long periods of time under intermittent wetting indicate that the moisture content in the depth LC significantly influences the total evaporation from the whole profile.

4.1.2 Evaporation stages 2 and 3: Evaporation in stage 2 is then considered to commence after the cumulative amount U has evaporated. Evaporation rate in this stage is independent of the evaporation potential of the atmosphere as long as this is high (Gardner and Hillel, 1962). Under these conditions it is controlled by unsaturated water flow to the soil surface.

Isothermal unsaturated water flow for bare soil has been shown to obey the partial differential equation

$$\partial\theta/\partial t = \partial/\partial x[D(\theta)\cdot\partial\theta/\partial x] \quad \text{-------- - - - -(1)}$$

where

θ =	volumetric moisture content	(L^3/L^3)
x =	distance	(L)
$D(\theta)$=	soil water diffusivity	(L^2/t)
t =	time	(t)

Equation 1 can be solved analytically assuming soil of infinite depth at uniform initial moisture content, and infinitely high atmospheric evaporation potential. Integrating, the solution with respect to x gives the cumulative evaporation E as follows (Crank, 1956; Black et al., 1969)

$$E = 2(\theta_i - \theta_0)(\bar{D}t/\pi)^{1/2} \quad \text{------------ - - - -(2)}$$

Where

E =	cumulative evaporation in stage 2	(L)
t =	elapsed time	(t)
D =	Weighted mean diffusivity	(L^2/t)
θ_i =	initial moisture content	(L^3/L^3)
θ_o =	air dry moisture content	(L^3/L^3)

Equation 2 can be written as:

$$E = Ct^{1/2} \quad \text{- - - - - -(3)}$$

where C is constant for a given soil.

Equation 3 states that cumulative evaporation is directly proportional to the square root of elapsed time. However, experiments have shown that this relationship holds only during the initial period of stage 2 evaporation and the constant C for a given soil depends on the depth of wetting and the ambient temperature.

Gardner and Gardner (1969) have shown that if equation (1) is put in a dimensionless form and E/M_i plotted against $(D_0t/L^2)^{1/2}$, the resulting curve is applicable to any depth of wetting. M_i is the total initial amount of water present for stage 2 evaporation, D_0 is the diffusivity of air dry soil, L is the depth of wetting and t is the elapsed time after onset of stage 2 evaporation. This approach gave reliable estimates of evaporation from bare soil during a single drying cycle from an initially wet soil of any depth. However, in the field the soil is wetted by rains of various magnitudes and frequencies. Modifications are necessary to adapt the above results to field situations.

4.1.3 Experiment: A field experiment to measure bare soil evaporation was carried out on a Ferric Luvisol at the Agricultural Research Station at Sebele, Botswana. Relevant soil profile characteristics are given in Table 5. A square plot of side 2m with a neutron access tube at the centre was wetted to field capacity to a depth of about 105 cm. The profile moisture was periodically monitored with a neutron moisture probe and water added necessary to wet the profile to the required depth. The plot was covered with plastic sheet to prevent evaporation and moisture was allowed to redistribute in the profile. When the profile reached field capacity, as ascertained by neutron probe observations, the plastic covering was removed and the profile was allowed to dry under natural atmospheric conditions. Soil moisture was monitored with the neutron moisture probe at 15cm depth increments. Initially, measurements were made at 1-day intervals and later increased to 2 and 3-day intervals as the evaporation rates decreased. The length of the drying cycle was 22 days.

4.1.4 Models and computations: The procedures and calculations adopted in the models are given below. The moisture content used in all calculations are expressed in depth units. All symbols are explained in the list attached.

1. For each measurement of profile moisture content, volumetric moisture content was plotted against depth (Figure 7). The cumulative evaporation was calculated with this data. This was plotted along with potential evapotranspiration (FAO 1977) against elapsed time (Figure 8). Using Figure 8, the maximum cumulative evaporation in stage 1 i.e. U was estimated as the cumulative evaporation up to the point where the cumulative evaporation curve departs from the cumulative potential evapotranspiration curve. The depth LC to which moisture depletion takes place in stage 1 evaporation is determined from Figure 7. From Figures 7 and 8, LC = 45cm. and U = 1.65cm.

2. Values of E and t were read off from Figure 8 to plot the dimensionless curve E/M_i versus $(D_0t/L^2)^{1/2}$ taking E=0 and t=0 for beginning of stage 2 evaporation. For simplification L is replaced by M_i since the depth of wetting is closely related to the initial amount of water. D_0 is also assumed to be equal to 1, since diffusivities of soils generally decrease to between 1 and 10 cm^2/day at the lower limit of wetness and the lowest value probably occurs at air-dry moisture (Hillel, 1980). Figure 9 shows the dimensionless curve of E/M_i versus $(t/M_i^2)^{1/2}$ for the Ferric Luvisol.

3. Moisture contents at saturation, field capacity, wilting point were estimated from moisture retention characteristics and bulk densities. In this study, field capacity was estimated by actual field measurements for 105 cm depth of wetting. The field capacity for depths LC and L are assigned the variables MXMC and

Table 5. Properties of Ferric Luvisol-Sebele, Botswana

Depth (cm)	Bulk density (g/cc.)	Moisture retention (vol %)			Particle size (wt %)						
		.1bar	.3bar	15bar	cS	mS	fS	vfS	cSi	fSi	Clay
0-33	1.66	15.4	12.0	6.5	28	21	21	11	2	3	19
33-69	1.55	15.8	12.29	9.3	32	21	18	8	2	2	23
69-138	1.54	20.6	17.2	9.8	18	17	21	13	3	2	26

Avg. measured field capacity for 0-105 cm : 16.5 (V%)

cS - Coarse sand
mS - Medium sand
fS - Fine sand
vfS - Very fine sand
cSi - Coarse silt
fSi - Fine silt

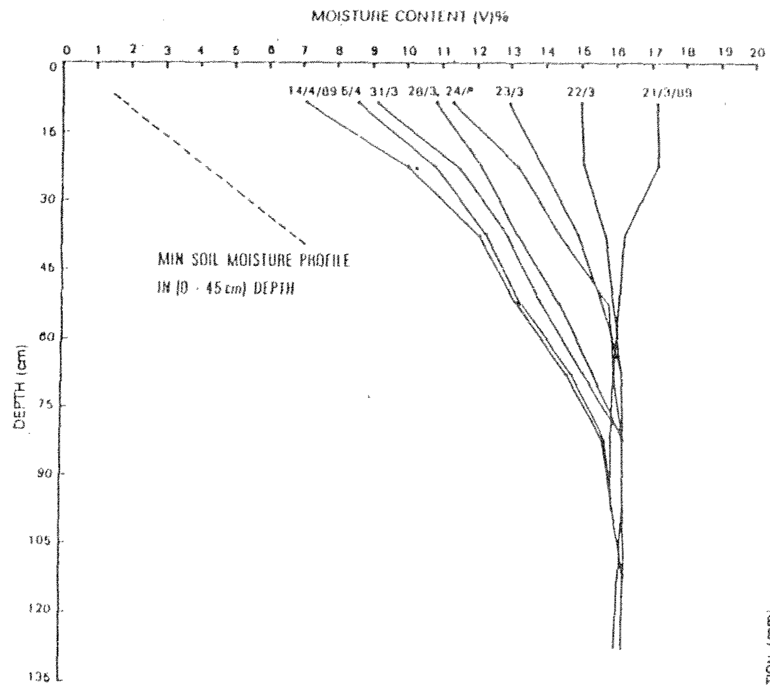


FIG 7 : DRYING MOISTURE PROFILES OF INITIALLY WET BARE SOIL

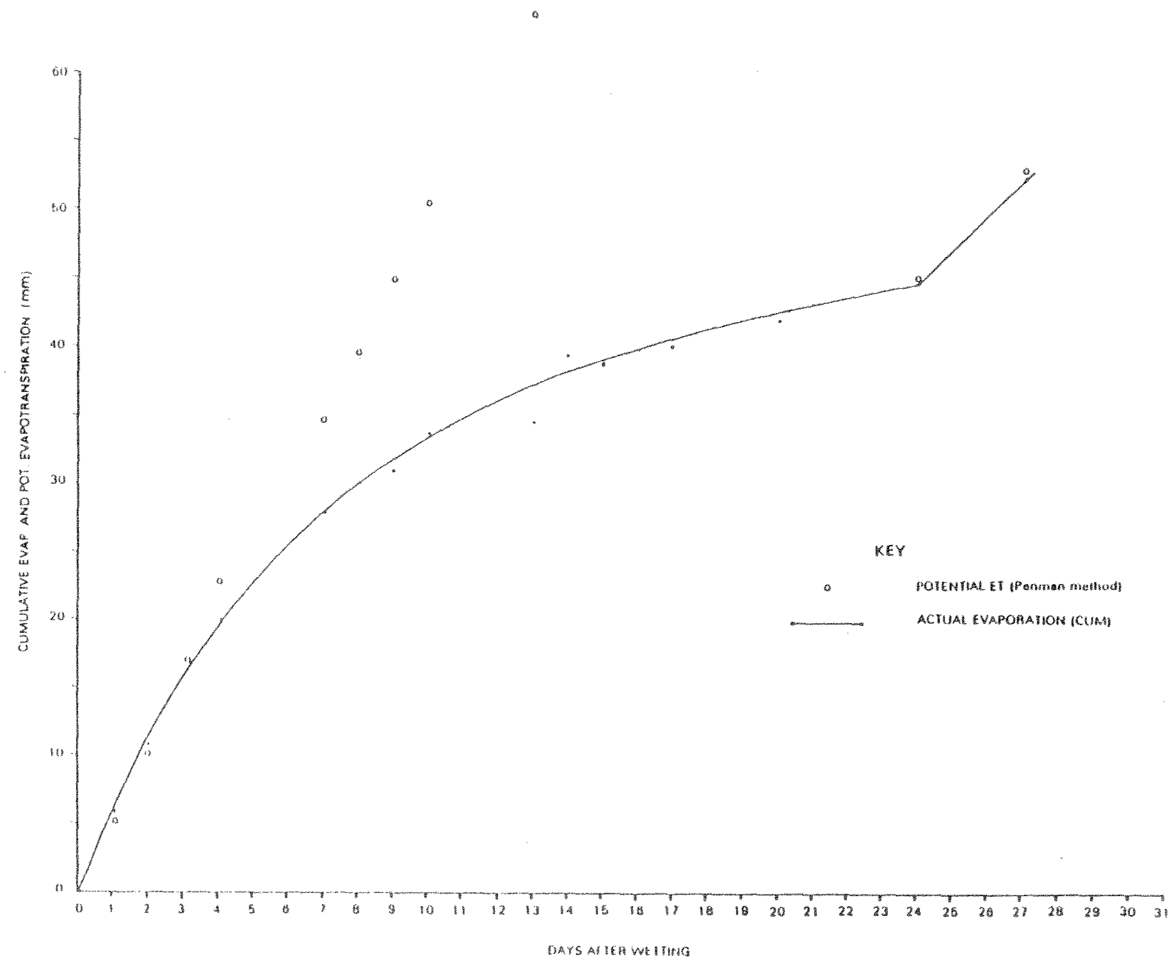


FIG 8 : CUMULATIVE EVAPORATION FROM AN INITIALLY WET BARE SOIL AND POTENTIAL EVAPOTRANSPIRATION

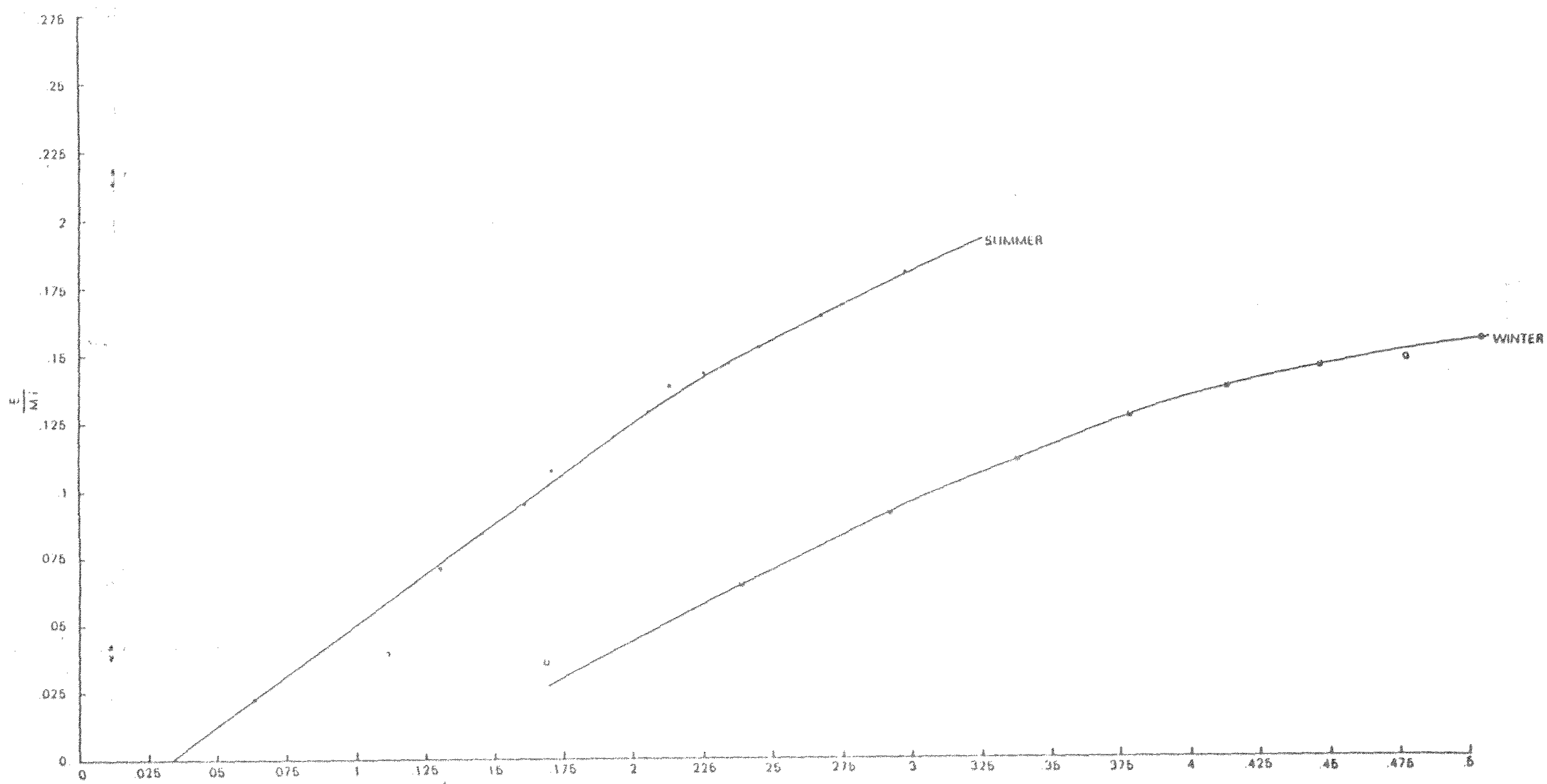


FIG 9: FRACTIONAL WATER LOSS COMPARED TO SQUARE ROOT OF TIME OF EVAPORATION IN DIMENSIONLESS FORM $(t/M_i^2)^{1/2}$

MX. The evaporation potential of the atmosphere is assumed to be equal to the potential evapotranspiration rate PET, as estimated by the Modified Penman's equation (FAO, 1977). This assumption seems appropriate for a wet soil as it has been shown that the reflection coefficient of wet soil is close to .2 and the roughness coefficient will be higher than that for free water. During the drying experiment, the soil was wet to field capacity initially and later on another occasion after a heavy rain. At both times as shown in Figure 8 the evaporation rate was equal to the PET thus supporting the assumption.

4. The foregoing results were used as inputs for a simplified model developed to calculate the water balance of the bare soil under actual rainfall for any period lengths such as daily, weekly, decadal etc. The model considered the soil profile as either of depth LC or L , depending on the depth of wetting and the moisture contents in depths LC and L after a rainfall. The steps in the calculations are shown below assuming the period length to be of 10 days.

[i] At the beginning of calculations, the model assumes that the profile moisture content is somewhere in a first cycle of evaporation from field capacity. From this starting initial moisture contents for depths LC and L, namely IMC and IM, the current stage of evaporation is determined from the total moisture deficit TES of the profile from field capacity MX:

$$TES = MX - IM$$

If TES < U, then the profile is in stage 1 evaporation. The remaining evaporation and its duration that is possible in stage 1 is U - TES and (U - TES)/PET respectively. Figure 9 is then used to read off E/M_i for $(t/M_i^2)^{1/2}$ to estimate E. E will be the stage 2 evaporation for the balance of the decade which will be the value for t in days.

Thus $t = 10 - (U - TES)/PET$ and $M_i = MX - U$

Total evaporation AE for the decade thus becomes

$$AE = (U - TES) + E$$

[ii] If TES > U, then the profile is in stage 2 evaporation and the moisture deficit E_1 in stage 2 is TES - U. Figure 9 is then used to read off $(t/M_i^2)^{1/2}$ for E_1/M_i to estimate t the elapsed time to reach the present moisture content. The elapsed time t is then extended by 10 days to calculate a new $(t/M_i^2)^{1/2}$. Figure 9 is again used to read off a new E_2/M_i for the new $(t/M_i^2)^{1/2}$. The evaporation AE for the decade is then

$$AE = E_2 - E_1$$

[iii] Having estimated the evaporation for the decade with no rainfall, the model then considers the total rainfall P for the decade as if all fell on the first day of the decade. The rainfall amount is separated into four categories.

a: The rainfall P is large enough to replenish the deficit partially or fully in the total depth L to bring the profile to stage 1 evaporation i.e. P > TES - U. (Figure 10a) In this case, the calculation goes back to step [i] to estimate evaporation for the new amount of soil moisture and discards the calculations of the earlier case with no rainfall.

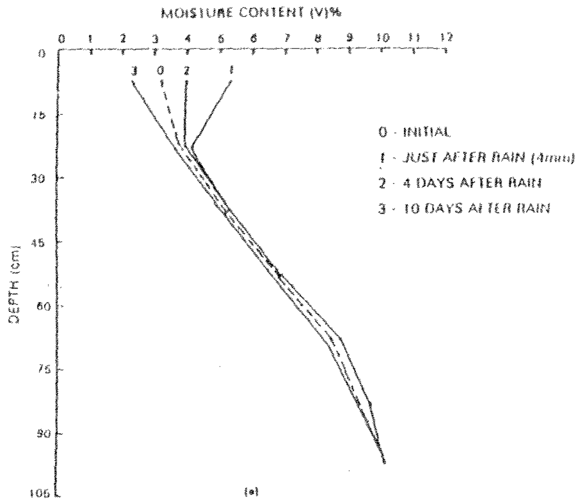
b: The rainfall P is large enough only to replenish the deficit in depth LC to bring it back to stage 1 evaporation i.e. P > TESC - U where TESC = MXMC - IMC. (Figure 10b). In such a case, the calculation goes back to step [i] but considers the profile as of depth LC, so that M_i = MXMC-U.

c: The rainfall P is small but cannot be evaporated in 2 days so that moisture penetrates to deeper layers (Figure 10c). The increased evaporation due to the wet surface soil layers is less than the rainfall (Gardner and Gardner, 1962; Ritchie, 1972). The evaporation in such cases varies from .6P to .9P and in this model it is taken as .6P based on actual observation. To this amount is added the evaporation from the profile as calculated by steps [i] or [ii] for the no-rainfall case to obtain the total evaporation for the decade.

d: The rainfall P is so small such that .6P is less than PET. i.e P < 1.8xPET. (Figure 10d) All the rainfall is taken to evaporate in addition to the evaporation that would occur without rainfall as in steps [i] or [ii]

In categories of rainfall b,c and d, the profile is considered to be of depth LC. The appropriate values of M_i and moisture deficits are then used to calculate the evaporation. The procedure is continued for the succeeding decades until the total evaporation exceeds the total moisture increase in LC. Experimental evidence (Gardner and Hillel, 1962; Gardner and Gardner,1969) indicate that for small additions of water, the evaporation proceeds according to the moisture content of the newly wetted layers till the added water is fully evaporated. (Figure 10e).

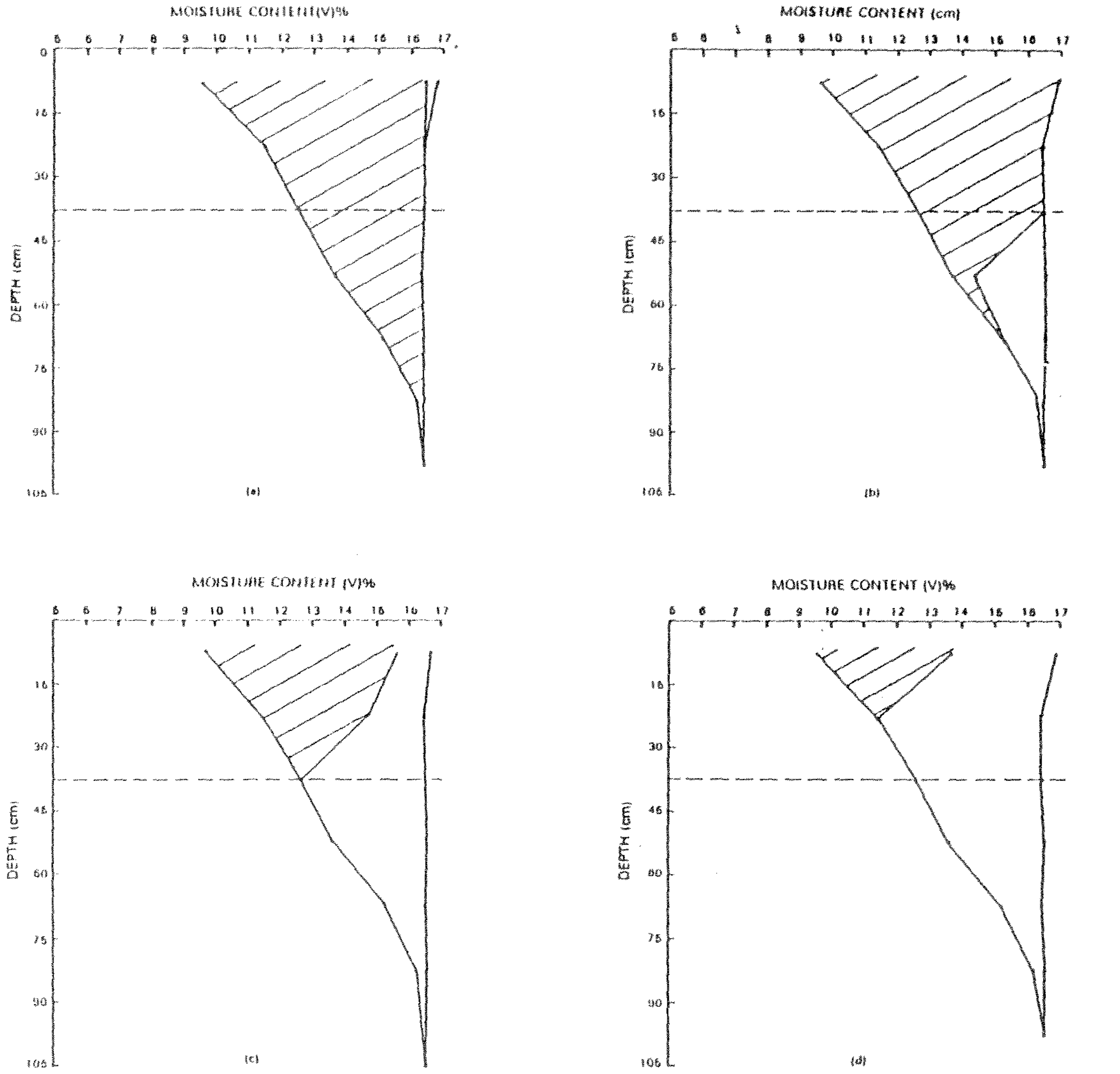
[iv] Once the evaporation for the decade is calculated, the initial moisture contents IM and IMC of the depths L and LC respectively are incremented by the rainfall P up to a maximum of soil saturation. Evaporation is then subtracted from these amounts to give the final moisture content in the depths L and LC. The final moisture content for the two depths become the initial moisture contents for the succeeding decade and the steps are repeated. An upper limit equal to field capacity is set for the initial moisture content.



DRYING MOISTURE PROFILE OF BARE SOIL AFTER RAIN WETTING SURFACE LAYER

CASE (a) RAIN REPLENISHES DEFICIT FULLY IN ENTIRE DEPTH OF PROFILE

CASE (b) RAIN REPLENISHES DEFICIT FULLY IN 0 - 45cm, AND PARTIALLY BELOW



CASE (c) RAIN REPLENISHES DEFICIT PARTIALLY IN 0 - 45cm

CASE (d) RAIN REPLENISHES DEFICIT PARTIALLY NEAR SURFACE ONLY

FIG 10: TYPES OF WETTED PROFILES FOR RAINFALL OF DIFFERENT MAGNITUDE

A lower limit of moisture content, MNMC, is introduced for depth LC because the surface layer never goes below the air-dry moisture content. The soil layers immediately below are also so dry that the evaporation is in the vapor phase. The moisture content in depth LC remains unchanged and any observed evaporation that occurs is from the lower depths. The value for MNMC is estimated by assuming that 0 - 15 cm depth of soil is air-dry and the moisture content profile in 0 - 45 cm depth is taken to be parallel to the last moisture content profile in the drying experiment (Figure 7). Although this method of estimating the minimum moisture content appears arbitrary, the values agree well with measured moisture contents during the driest periods. The minimum moisture content for Ferric Luvisol was 1.45 cm in the 0 - 45 cm depth.

4.1.5 Results and discussions: The procedures for predicting the cumulative evaporation from bare soil presented above was applied to 2 sites monitored during the 1988/89 growing season. The two sites were separated by a distance of 2 km. Daily rainfall was measured separately near the two sites. Actual evaporation was estimated by water balance of the two sites using weekly profile moisture contents measured by a neutron moisture probe. There was no run- off from rainfall except on one occasion when the rainfall was high enough to charge the profile to near field capacity. Evaporation after this rainfall event was treated separately. Moisture content measurement at lower depths indicated no water loss by deep percolation.

Figures 11 and 12 show the predicted and measured cumulative evaporation from the two Ferric Luvisol profiles from 10-10-88 to 23-3-89. Considering the fact that the variability associated with moisture content measured by neutron moisture probe is greater than by other accurate methods such as lysimeters, the agreement between predicted and measured evaporation is good. In both cases the predicted and measured evaporation follow the same trend. Figure 13a show the predicted cumulative daily evaporation calculated using daily rainfall records and plotted against weekly measured evaporation. Figure 13b show the predicted cumulative weekly evaporation for the same period but was calculated assuming that the total rainfall for the week fell on the first day of the week. Although the predicted and measured evaporation generally is in agreement in both cases, the agreement is better in the latter case when the rainfall is taken as a single event on the first day of the week.

These predicted evaporation data can be used to estimate soil moisture content by simple water balance, assuming that the rainfall is totally effective and the run-off is negligible. The estimated soil moisture storage should not be expected to fully match the measured point values because the model assumes a single rainfall event at the beginning of the period of calculation. However, the measured and the predicted soil moisture storage

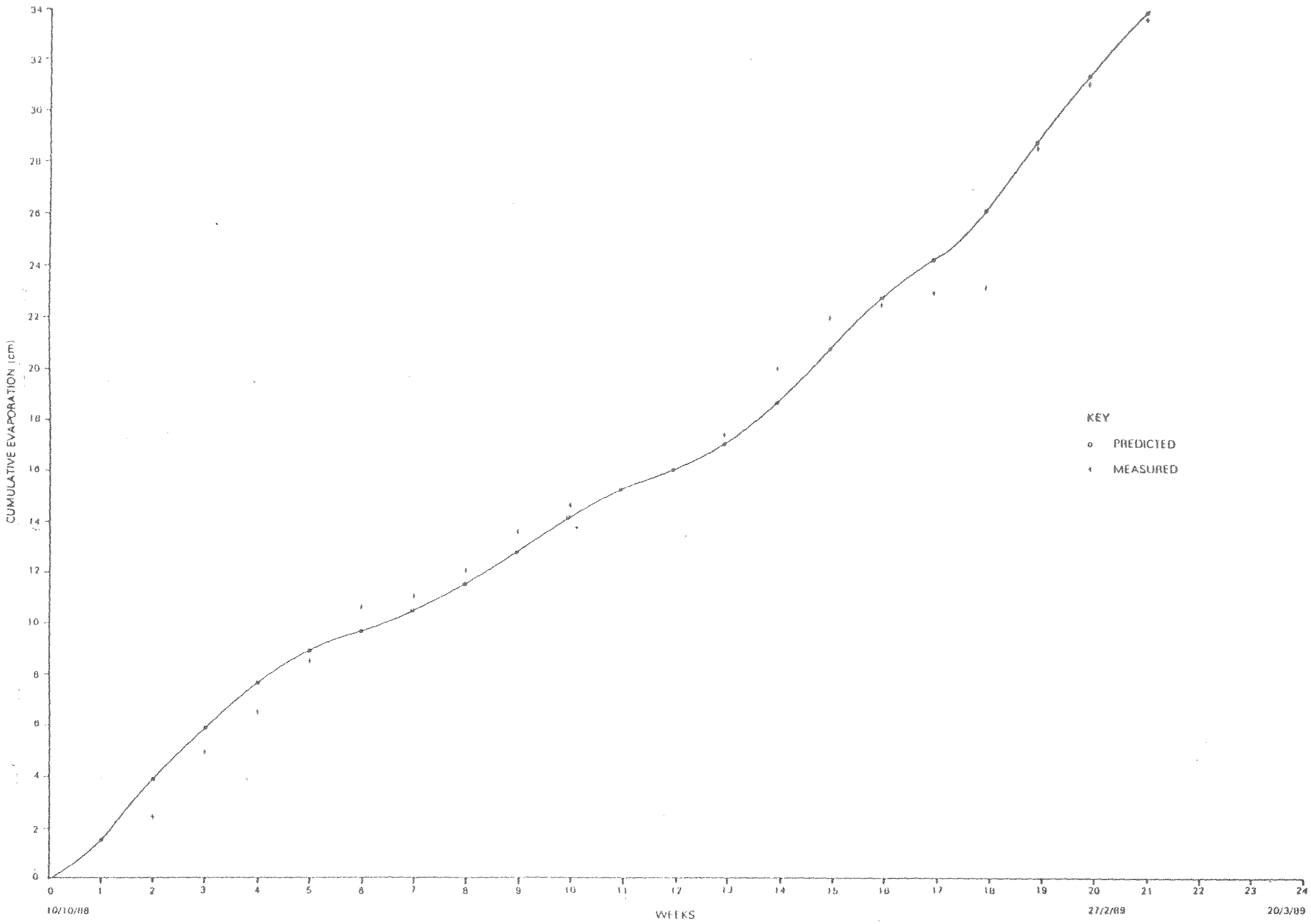


FIG11: MEASURED AND PREDICTED CUMULATIVE EVAPORATION FROM BARE SOIL (Ferric Luvisol Site 1)

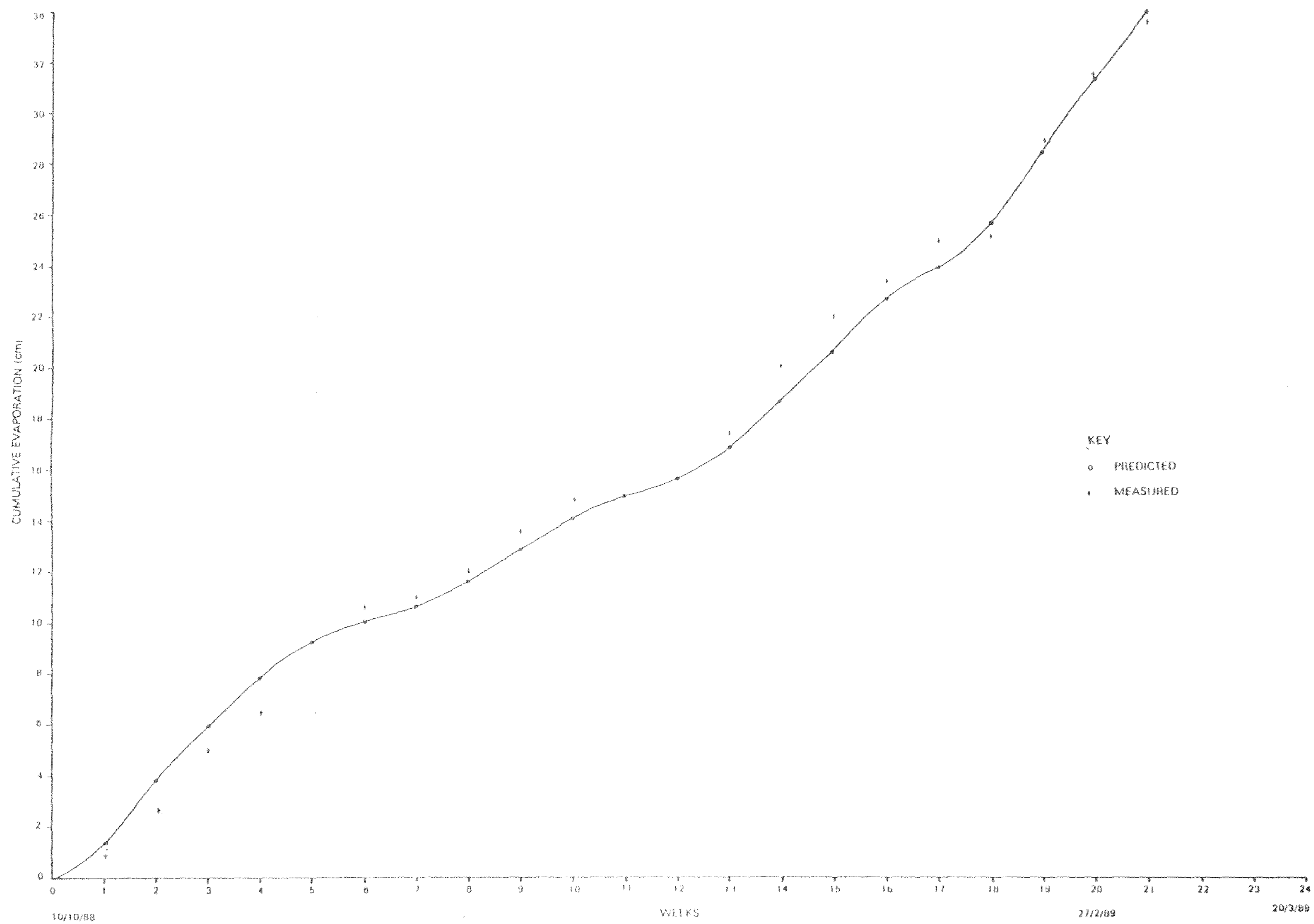
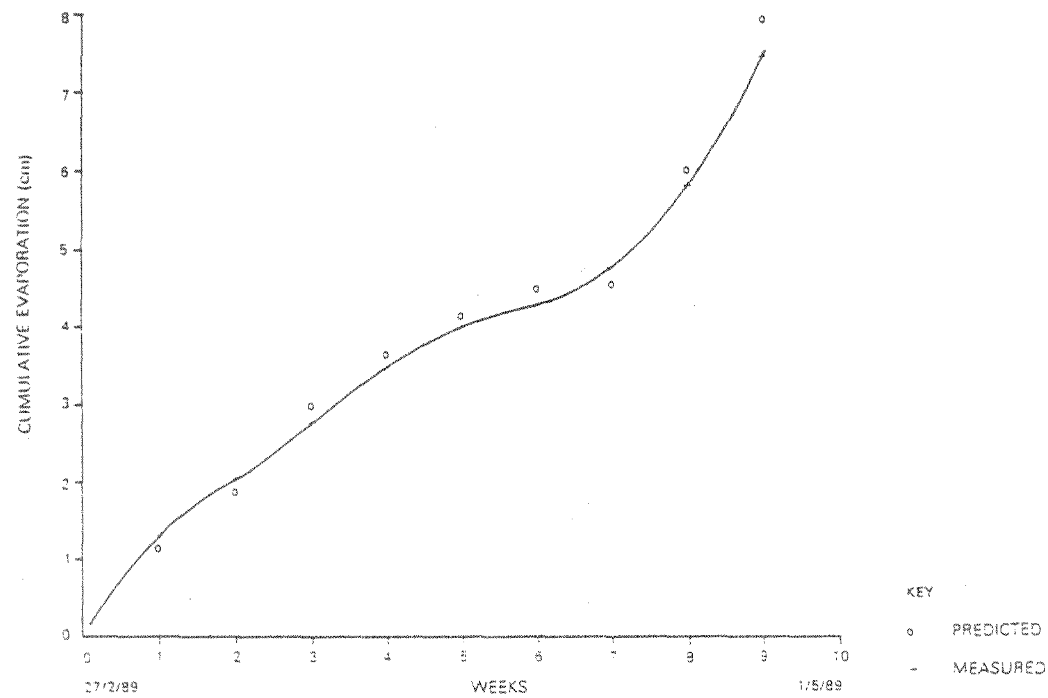


FIG 12: MEASURED AND PREDICTED CUMULATIVE EVAPORATION FROM BARE SOIL (Ferric Luvisol - Site 2)

FIG 13b: CUMULATIVE EVAPORATION CALCULATED ON WEEKLY RAINFALL TOTALS AND WEEKLY MEASURED EVAPORATION



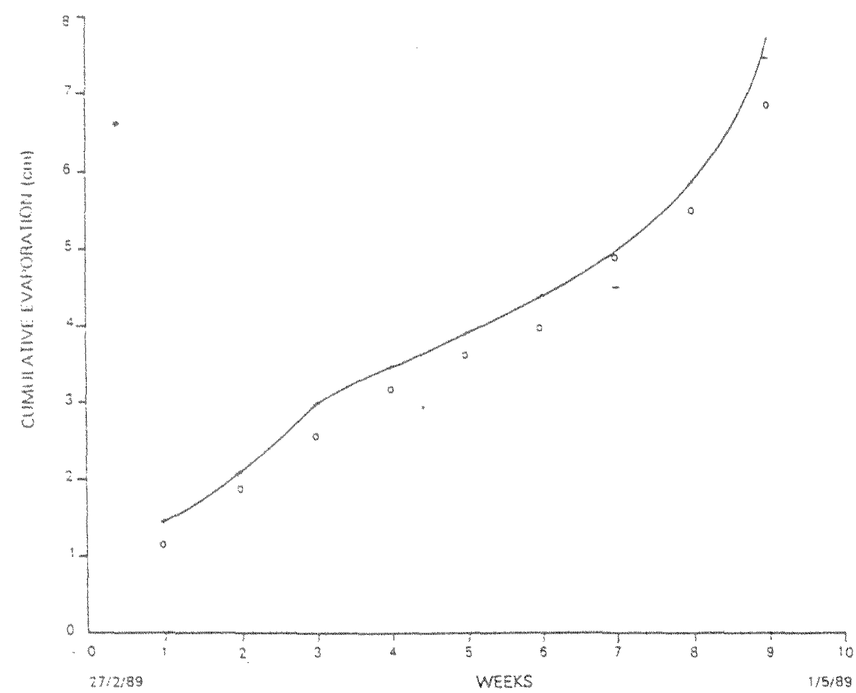


FIG13a: CUMULATIVE EVAPORATION CALCULATED ON DAILY RAINFALL DATA AND WEEKLY MEASURED EVAPORATION

should follow the same trend without much deviations. Figures 14 and 15 show the predicted and measured weekly variations of soil moisture content in the 0 - 45 cm and 0 - 105 cm depth for the two profiles for which evaporation was calculated. The agreement is good for practical purposes. This approach can also be readily be applied to keep a soil moisture budget during any season. As the season progresses, daily or decadal rainfall totals at the end of the period can be used with the profile moisture of the preceding period in the model. The initial input of profile moisture necessary at the beginning of the season can be actually measured or assumed to be the average value from historical data.

The proposed technique for estimating evaporation from bare soil works well for weekly or decadal periods. Most of the inputs are the soil physical properties that are normally measured in soil characterization. However, a field measurement of a single cycle of evaporation is necessary to derive the dimensionless plot of E/M_i vs $(t/M_i^2)^{1/2}$ and few other parameters. This measurement may appear to be a limitation for the application of the methodology. However, in the routine characterization of soils for their physical properties, field measurements are carried out to determine bulk density, infiltration and hydraulic conductivity. One additional measurement of evaporation of a wet soil profile is all that is necessary for use in the above methodology. Gardener (1974) obtained data from a drying experiment in the laboratory using an undisturbed soil column to derive the dimensionless curve. He used these results successfully to predict evaporation from a bare soil. If it can be established that the results from field and laboratory measurements are comparable, then obtaining the dimensionless plot of cumulative evaporation versus square root of time for any soil using undisturbed soil columns in the laboratory will be much easier.

4.2 Evapotranspiration deficit and yield reductions

Evapotranspiration from crops, proceeds at the maximum possible rate ET_m, when the water supply from the soil is not limiting. When the soil dries, water supply to the plant roots become limiting, the actual evapotranspiration rates ET_a decreases and the physiological activities of the plant is reduced. Maximum yield, Y_m is the yield that can be achieved when the evapotranspiration rates are maintained at the maximum. The actual yield Y_a is lower when evapotranspiration is deficit

The relative yield decrease due to relative evapotranspiration deficit is quantified according to the equation (FAO,1979)

$$1 - Y_a/Y_m = K_y(1 - ET_a/ET_m) \quad - - - - - - - - - (4)$$

where

Y_a = actual harvested yield (M)

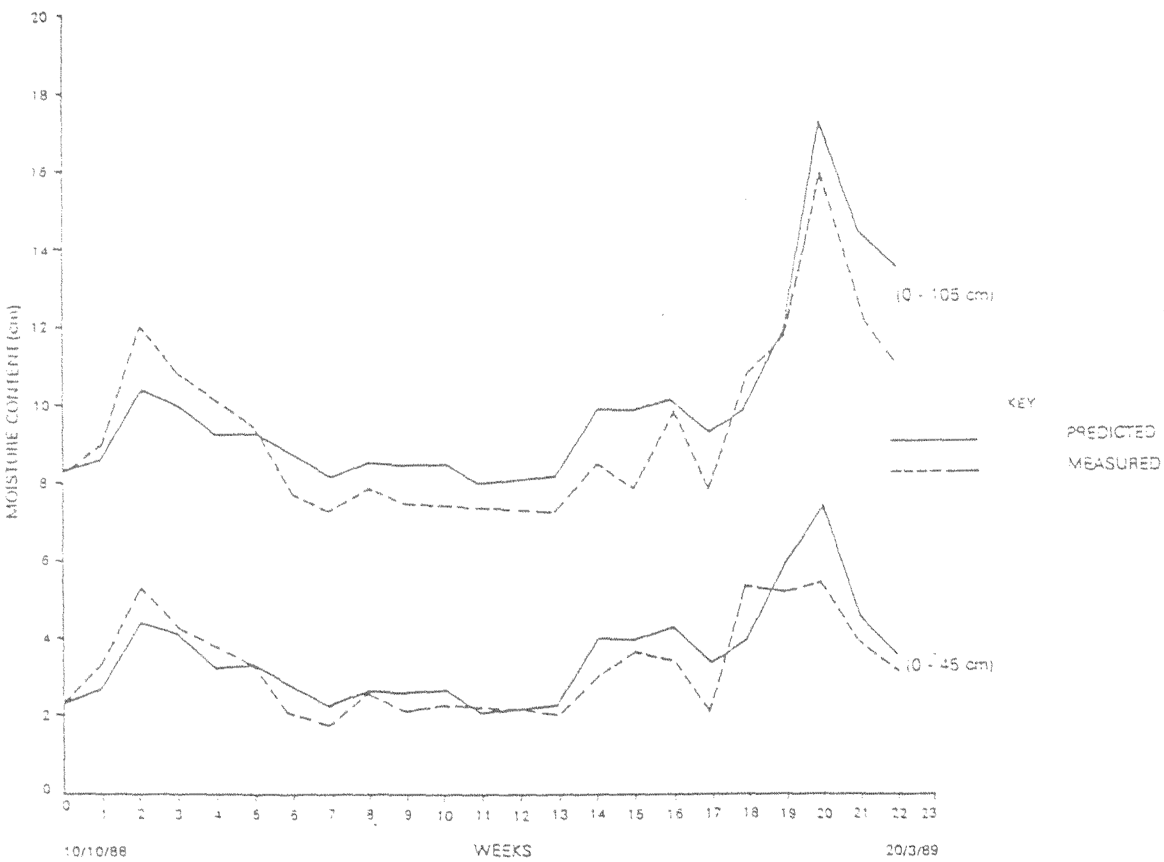


FIG 14: VARIATION OF SOIL MOISTURE WITH TIME FOR TWO DEPTHS (0 - 45 and 0 - 105 cm) Site 1

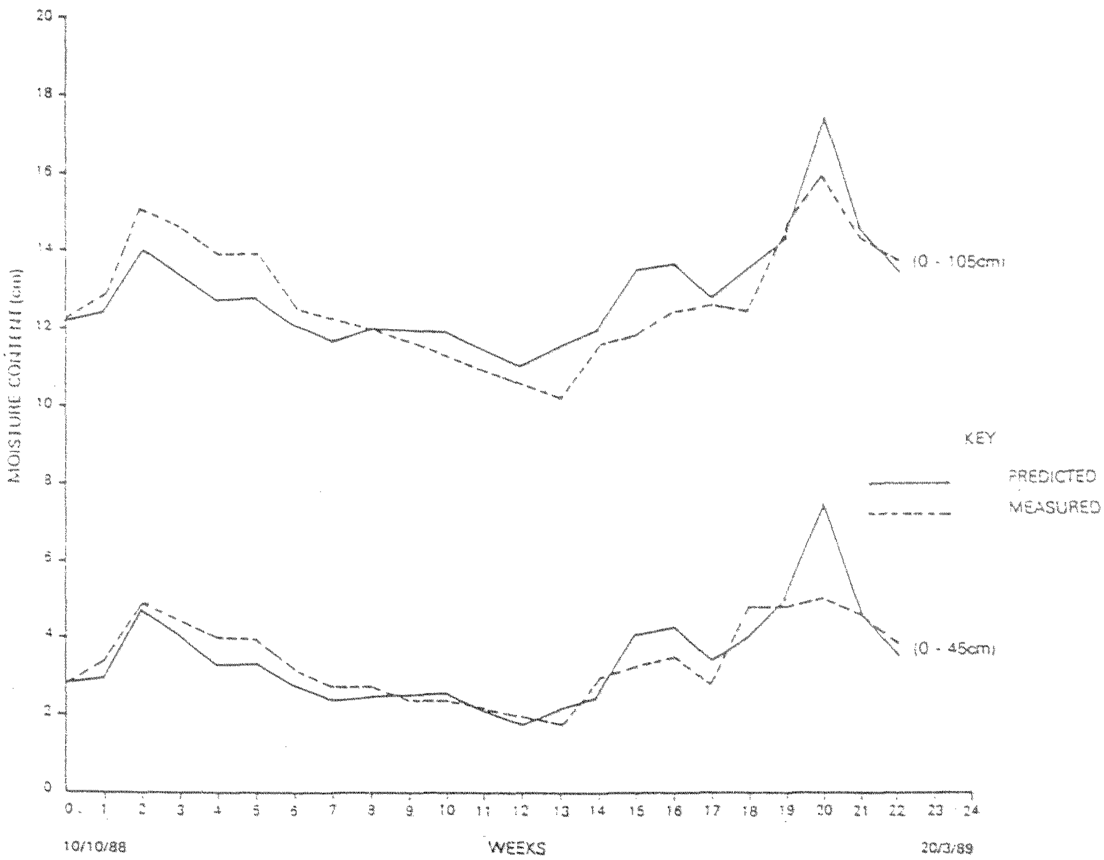


FIG 15: VARIATION OF SOIL MOISTURE WITH TIME FOR TWO DEPTHS (0 - 45 and 0 - 105 cm) - Site 2

Y_m = maximum harvested yield (M)
K_y = yield response factor (dimensionless)
ET_a = actual evapotranspiration (L)
ET_m = maximum evapotranspiration (L)

The value of the yield response factor Ky is specific for the crop and its stage of growth development. Moisture stress of a given magnitude may occur in any of the crops' growing period. The relative magnitude of the K_y factors reflects the sensitivity of the growth period to moisture stress in reducing yields.

Equation 4 shows that if the actual evapotranspiration ET_a for a given soil moisture can by estimated, and if ET_m and K_y are known, then the potential yield can by readily estimated as a percentage of the maximum.

4.2.1 Models and computations

Reliable methods for the estimation of ET_a and ET_m have been developed and published by FAO (1977,1979). These publications give all the necessary inputs including K_y values for different crops. Detailed procedures are described for estimating yield decrease caused by evapotranspiration deficit according to equation 4. The FAO methods (1977, 1979) for estimating yield reductions from evapotranspiration deficits were adapted for actual rainfall conditions. The procedure used is summarized below.

[i] Maximum evapotranspiration $ET_m = K_c \times ET_0$ where K_c is the crop coefficient specific for the crop and its growth stage. ET_0 is the reference crop evapotranspiration calculated according to modified Penman's method (FAO 1977)

[ii] Actual evapotranspiration ET_a depends on the amount of available moisture in the root zone. ET_a is calculated according to the method proposed by Rijtema and Aboukaled (1975) and adopted by Joshua (1986). The method is based on simple water balance taking into account the initial moisture storage, rainfall, available moisture holding capacity in the root zone and maximum evapotranspiration rate.

[iii] The planting opportunities were defined under 3 categories based on the amount of available soil moisture storage in the surface layer (0-45 cm in Ferric Luvisol)

Level 1 Equivalent to 50 percent or more of total available moisture of 0 - 45 cm depth of soil. (>56 mm.)

Level 2 Equivalent to 50 percent or more of total available moisture of 0 - 30 cm depth of soil.

(50 - 56 mm.)

Level 3 Equivalent to 50 percent or more of total available moisture of 0 - 15 cm depth of soil. (44 -50 mm.)

These three level of moisture storage was chosen mainly to establish a minimum storage that is necessary to prevent crop failure under the existing rainfall regime. The three levels of moisture storage assumes sufficient moisture for seed germination but differ in their ability to sustain growth in the following decades without rainfall.

[iv] Sorghum was used as the test crop to simulate the yield on a Ferric Luvisol using 40 years of historical rainfall records for Gaborone. Initially soil moisture contents in 0 - 45 cm and 0 - 100 cm depths at the beginning of each decade from September 1949 to September 1989 was determined. The methodology described above for estimating bare soil evaporation was used for this purpose. Decades with planting opportunities between November and February were selected to simulate sorghum growth, actual evapotranspiration, evapotranspiration deficit and relative yield. The results give the actual yield as a percentage of the maximum possible yield for each decade with a planting opportunity.

4.2.2 Results and discussions:

Planting opportunities: The results from the simulation of bare soil evaporation carried out for the 40 years indicate that at the end of winter there was no available soil moisture storage in the profile. The moisture content in the 0-45 cm depth was minimum at this time for almost all the years. In some years, even late August rains could not build up the moisture storage to above wilting point. Table 6 shows the frequency of the three levels of soil moisture storage that occurred during the 40 years for each decade. The probability for having planting opportunities increases from the second decade of November to a maximum in the third decade of January. In February there are many planting opportunities. However, late plantings may cause yield reduction due to low minimum temperatures during critical growth stages as the season advances. Interestingly, in most of the decades where there were significant number of planting opportunities, the majority of them were at the highest level of moisture storage. This indicates that the rainfall generally is in spells of substantial amount rather than being small and intermittent

Moisture availability and yields: The growth stage or stages during which plants undergo moisture stress is important in determining the degree of yield depression. Some growth stages of a crop are more sensitive to moisture stress than the others. For a 120-day Sorghum crop, the most sensitive periods are the flowering and

Table 6. Frequency of planting opportunities at three levels of soil moisture storage in 0-45 cm depth during 1949-1989 growing seasons.

Month	Decade #	Planting opportunities			
		level 1	level 2	level 3	total
Sept	1	0	0	0	0
	2	0	0	0	0
	3	0	1	0	1
Oct	1	0	0	3	3
	2	0	1	1	2
	3	2	1	2	5
Nov	1	1	1	2	3
	2	8	0	3	11
	3	7	1	2	10
Dec	1	7	3	3	13
	2	11	3	3	17
	3	9	4	0	13
Jan	1	10	3	3	16
	2	9	3	4	16
	3	11	1	7	19
Feb	1	14	2	2	18
	2	9	2	3	14
	3	8	2	6	16
March	1	8	1	7	16
	2	8	1	6	15
	3	8	2	3	13
April	1	2	4	4	10
	2	3	1	4	8
	3	6	0	2	8

Level 1 :- moisture > 56mm
Level 2 :- moisture > 50mm
Level 3 :- moisture > 44mm

grain forming stages. These two sensitive growth stages commence in about 30-40 days after germination and continue for further 60 days. Although the initial soil moisture storage is important for germination, the subsequent rainfall distribution is critical in determining the actual yields. Table 7 shows yields that would have been possible for the 40 years if sorghum was planted on planting opportunities i.e. decades that had adequate soil moisture storage. Clearly, in each year there were more than a single planting opportunity but the yields varied according to the subsequent rainfall distribution. Highest yields do not correspond to the highest level of moisture storage during planting. In eight of the 40 years (20%), the rainfall was insufficient to build up the soil moisture storage to levels adequate for planting. For the remaining 32 years, the potential yields for each year's rainfall distribution, varied from 13% to 80% of the maximum. The simulated yield data also indicate that there is a seventy-five percent probability of getting yields greater than 20% of the maximum. At fifty percent probability, yields are greater than 45% of the maximum. The maximum yield in Ferric Luvisol under good management and adequate water supply is in the range of 6-7 tonnes per hectare.

From Table 7, it can be seen that out of the 32 years with planting opportunities ,14 years had many consecutive decades in December and January for which planting was possible. When the yields for these decades were compared for each year separately, 9 out of the 14 years had the maximum yield corresponding to the second decade of December.Therefore it appears that planting around the second decade of December has the optimum probability for giving the best results.

The simulated yield results obtained with historical rainfall data can be used to assess the feasibility of rainfed agriculture in an area. Such results can also be used to quantify moisture availability as a land quality in land evaluation procedures. Different soils in an area will respond differently for the same land use under a particular rainfall regime. If the predicted yields are used as a basis for setting up criteria for suitability classes of moisture availability, then appropriate suitability classes can be assigned to the different soils according to the predicted yields.

<u>Management strategies for rainfed agriculture:</u> The two methodologies presented can be used together to predict the relative yields that could be expected for any crop on a given soil. The maximum yield that is possible with adequate water supply and good management can be generated through research trials in agricultural stations. With this information, the actual possible yields can be readily estimated. Decisions can then be made as to whether these yields are economically viable. If the yields are satisfactory, the strategies have to be directed towards the maximum utilization of rainfall through appropriate methods.

Table 7. Soil moisture storage levels(S) and corresponding yields(Y) as % of maximum for decades with planting opportunities between November and February (1949-1989)

Growing season		Soil moisture levels and yield percentages											
		November			December			January			February		
		1	2	3	1	2	3	1	2	3	1	2	3
49/50	S	-	-	-	-	1	1	1	1	1	-	-	-
	Y	-	-	-	-	44	44	47	45	48	-	-	-
50/51	S	-	3	-	-	-	1	1	2	1	3	-	-
	Y	-	48	-	-	-	33	38	47	57	63	-	-
51/52	S	-	3	-	-	-	-	-	-	-	-	3	-
	Y	-	42	-	-	-	-	-	-	-	-	27	-
52/53	S	-	-	-	3	1	1	1	2	3	-	-	-
	Y	-	-	-	50	55	54	48	47	41	-	-	-
53/54	S	-	-	-	-	-	-	-	1	3	-	-	-
	Y	-	-	-	-	-	-	-	56	48	-	-	-
54/55	S	-	-	-	-	-	-	1	3	3	2	1	-
	Y	-	-	-	-	-	-	37	31	28	27	35	-
55\56	S	-	-	-	1	1	1	1	2	1	-	1	-
	Y	-	-	-	47	52	39	27	27	25	-	20	-
56/57	S	3	1	-	-	-	-	-	-	3	-	-	-
	Y	48	53	-	-	-	-	-	-	31	-	-	-
57/58	S	-	-	-	-	-	-	-	1	1	1	2	-
	Y	-	-	-	-	-	-	-	34	31	26	24	-
58/59	S	-	1	-	-	1	2	3	-	-	-	-	-
	Y	-	35	-	-	29	25	29	-	-	-	-	-
59/60	S	-	-	-	-	1	-	-	-	-	2	-	-
	Y	-	-	-	-	25	-	-	-	-	25	-	-
60/61	S	-	1	1	1	1	1	1	3	-	1	-	-
	Y	-	52	52	44	46	53	61	45	-	63	-	-
61/62	S	-	-	-	-	-	-	-	-	-	-	-	-
	Y	-	-	-	-	-	-	-	-	-	-	-	-
62/63	S	-	-	2	2	-	-	-	-	-	3	-	-
	Y	-	-	24	21	-	-	-	-	-	23	-	-

Cont.

Table 7. Soil moisture storage levels(S) and corresponding yields(Y) as % of maximum for decades with planting opportunities between November and February (1949-1989) --Continued

Growing season		Soil moisture levels and yield percentages											
		November			December			January			February		
		1	2	3	1	2	3	1	2	3	1	2	3
63/64	S	-	-	1	-	-	-	-	-	-	-	-	-
	Y	-	-	31	-	-	-	-	-	-	-	-	-
64/65	S	1	1	3	3	-	2	-	-	-	-	-	-
	Y	28	29	26	22	-	21	-	-	-	-	-	-
65/66	S	-	-	-	-	-	-	-	-	-	-	-	-
	Y	-	-	-	-	-	-	-	-	-	-	-	-
66/67	S	-	-	-	-	-	-	-	1	1	1	1	-
	Y	-	-	-	-	-	-	-	72	74	72	62	-
67/68	S	-	-	-	-	-	-	-	-	-	-	-	-
	Y	-	-	-	-	-	-	-	-	-	-	-	-
68/69	S	-	-	-	-	-	-	-	-	-	-	-	-
	Y	-	-	-	-	-	-	-	-	-	-	-	-
69/70	S	-	-	-	-	-	-	-	-	-	-	-	-
	Y	-	-	-	-	-	-	-	-	-	-	-	-
70/71	S	-	-	-	-	-	-	2	-	2	1	1	-
	Y	-	-	-	-	-	-	41	-	40	37	31	-
71/72	S	-	-	1	1	2	-	-	1	1	1	-	-
	Y	-	-	51	40	40	-	-	24	23	20	-	-
72/73	S	-	-	-	-	-	-	-	-	-	-	-	-
	Y	-	-	-	-	-	-	-	-	-	-	-	-
73/74	S	-	-	-	-	1	1	2	-	1	1	1	-
	Y	-	-	-	-	78	71	58	-	41	35	27	-
74/75	S	-	1	1	1	1	1	1	3	1	1	2	-
	Y	-	62	64	64	64	66	70	79	80	83	75	-
75/76	S	-	-	-	3	3	1	1	1	1	1	1	-
	Y	-	-	-	73	69	71	72	65	52	51	42	-
76/77	S	-	1	1	2	1	1	1	-	3	1	-	-
	Y	-	62	67	65	65	54	49	-	36	24	-	-

Cont.

Table 7. Soil moisture storage levels(S) and corresponding yields(Y) as % of maximum for decades with planting opportunities between November and February (1949-1989) --Continued

Growing season		Soil moisture levels and yield percentages											
		November			December			January			February		
		1	2	3	1	2	3	1	2	3	1	2	3
77/78	S	-	-	-	-	2	2	1	1	1	1	3	-
	Y	-	-	-	-	50	48	39	31	27	26	24	-
78/79	S	-	-	-	-	-	-	-	-	3	1	-	-
	Y	-	-	-	-	-	-	-	-	19	21	-	-
79/80	S	-	-	-	-	3	-	3	1	1	1	1	-
	Y	-	-	-	-	67	-	44	38	31	24	19	-
80/81	S	-	-	-	2	2	-	-	-	-	1	1	-
	Y	-	-	-	68	70	-	-	-	-	30	24	-
81/82	S	-	-	1	1	3	-	-	-	-	-	-	-
	Y	-	-	35	32	33	-	-	-	-	-	-	-
82/83	S	-	3	-	1	1	-	-	1	3	-	-	-
	Y	-	34	-	25	26	-	-	22	20	-	-	-
83/84	S	-	-	-	-	-	-	-	-	-	-	-	-
	Y	-	-	-	-	-	-	-	-	-	-	-	-
84/85	S	3	-	-	-	-	-	-	-	-	-	-	-
	Y	20	-	-	-	-	-	-	-	-	-	-	-
85/86	S	-	-	-	-	-	-	-	-	-	1	1	-
	Y	-	-	-	-	-	-	-	-	-	16	17	-
86/87	S	-	1	3	-	-	-	-	-	-	-	-	-
	Y	-	28	30	-	-	-	-	-	-	-	-	-
87/88	S	-	-	-	-	-	-	2	-	-	-	-	-
	Y	-	-	-	-	-	-	77	-	-	-	-	-
88/89	S	-	-	-	-	-	-	-	3	-	-	-	-
	Y	-	-	-	-	-	-	-	43	-	-	-	-
89/90	S	-	1	1	1	1	2	3	-	3	-	3	-
	Y	-	51	47	45	39	41	42	-	36	-	32	-

Contour ridges to intercept run-off, tied contour furrows, timely sowing, are some methods that could be adopted. If the rainfall is insufficient to obtain economic yields, then methods have to be developed to increase moisture availability through water harvesting. Cultivation of only the lower sites which receive run-off from upper positions in the landscape is one such method.

The results in Table 6 can be used to arrive at an optimum planting time for the existing rainfall pattern. In the case of sorghum, for example, moisture stress during the flowering and the yield forming stages should be minimum. Table 6 shows that high probabilities for obtaining adequate soil moisture storage for planting are between the second decade of December and the first decade in February. However rainfall probabilities (Figure 16) show that there are two distinct peaks, one in late November and the other in mid January. Therefore it appears that the optimum sowing time for sorghum would be during the second and the third decades of December so that the sensitive period to moisture stress falls in the second peak in mid January. As seen earlier, the results from the predicted yields supports this inference.

4.3 Conclusions

In areas of limited rainfall the use of the methodology to estimate evaporation from bare soil works well for time periods of a few days or more. An essential condition is that the rainfall accounts fully for the increase in moisture content and run-off is considered negligible. The soil moisture storage calculated by the water balance of the profile assumes no deep percolation losses. These conditions prevail generally under semi-arid conditions. A different plot of E/M_i vs $(t/M_i^2)^{1/2}$ would have to be obtained for each type of soil.

2. The methodologies for bare soil evaporation and yield response to water used together can simulate growth and performance of crops on any soil under the existing rainfall pattern. The procedures shown can be adopted to estimate

(a) Year by year variation in soil moisture storage and moisture content at the start of the growing season.

(b) soil moisture storage at any time during a growing season by maintaining soil moisture budget.

(c) occurrence of suitable planting opportunities in the growing season.

(d) yield relative to that which could be achieved when moisture is not limiting.

(e) land suitability rating for moisture availability.

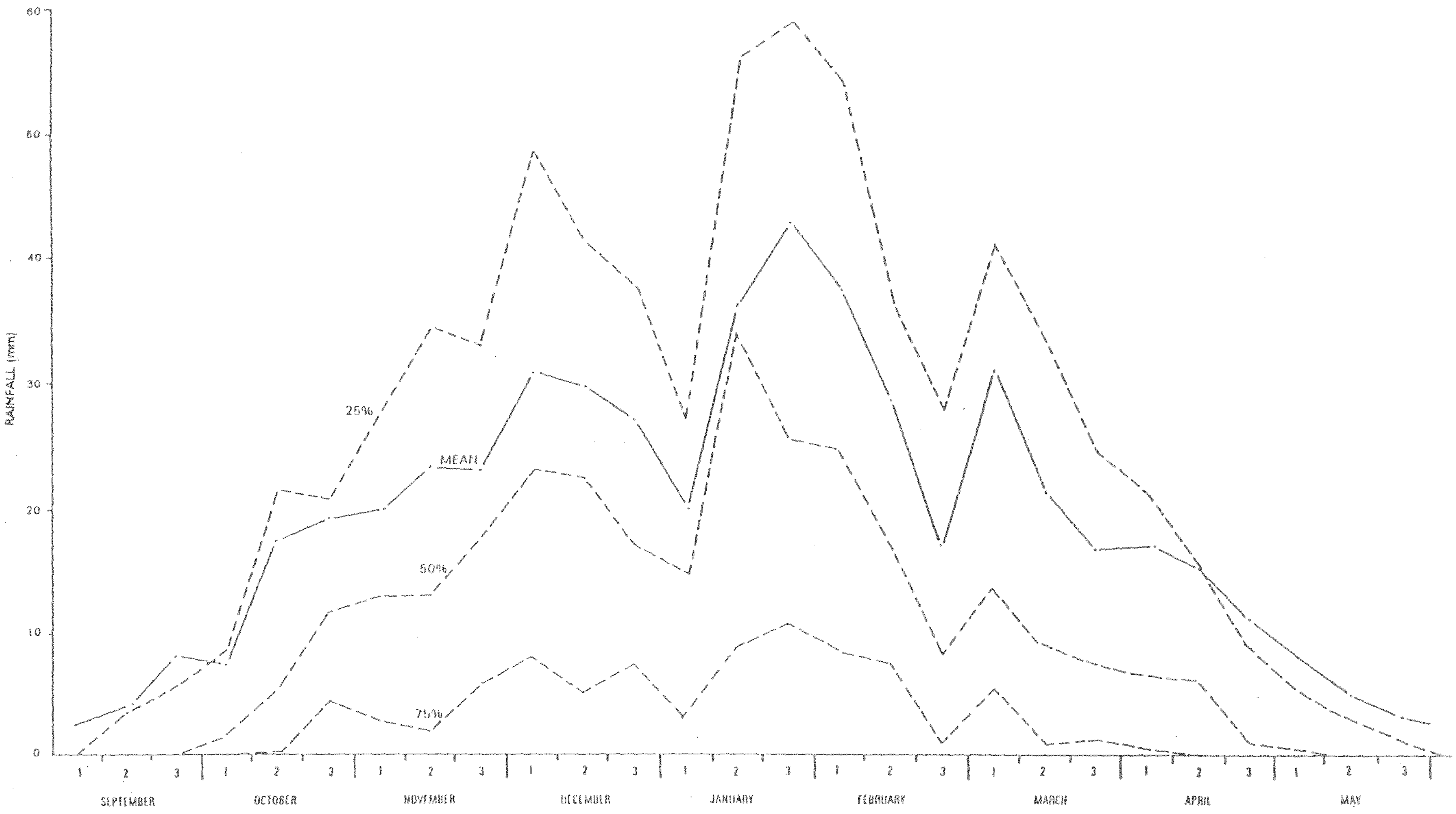


FIG 16: GABORONE RAINFALL (1925 - 1984) MEAN 10 DAY RAINFALL AND 25%, 50% & 75% PROBABILITIES

Notation

All moisture contents are expressed in depth units.

AE	-	Total evaporation for the period of calculations.
D_0	-	Diffusivity of the air-dry soil.
E	-	Cumulative evaporation in stage 2 drying.
IM	-	Initial moisture content in depth L at the beginning of the period of calculation.
IMC	-	Initial moisture content in depth LC at the beginning of the period of calculation.
L	-	Total depth of wetted profile.
LC	-	Maximum depth from the soil surface to which moisture depletion takes place during stage 1 drying.
M_i	-	Initial amount of water in wetted depth at the beginning of stage 2 drying. M_i = MX - U
MX	-	Maximum moisture content in depth L. i.e. moisture amount at field capacity.
MXMC	-	Maximum moisture content in depth LC. i.e. moisture amount at field capacity.
P	-	Total rainfall for the period of calculation.
PET	-	Potential evapotranspiration rate.
t	-	Total elapsed time in stage 2 drying.
TES	-	Total moisture deficit from field capacity in depth L. TES = MX - IM
TESC	-	Total moisture deficit from field capacity in depth LC. TESC = MXMC -IMC
U	-	Upper limit of cumulative evaporation from soil during stage 1 drying.

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ANNEX 1

SOIL PROFILE DESCRIPTION — Profile: G 0901 Unit: G 10b Status: I

SHEET : 242502
LOCATION : Sebele, Agricultural Research Center.
AUTHOR(S): A.B.Price M.D.Mays A.Remmelzwaal
CLASSIFICATION FAO: Haplic Lixisol(1988) Ferric Luvisol (1974)
ST : kandic Paleustalf ; fine loamy mixed hyperthermic

GRID : LC-929-826
COORD: 24-33-40-S 25-56-40-E
DATE : 12/04/86

AGRO CLIM.ZONE: 1E3
ELEVATION : 1015 m
SMR: ustic

LANDFORM : plain
TOPOGRAPHY: almost flat
SURF. CHAR: slight sealing, no cracks, nil evidence of salt,
LAND USE: improved trad. dryland farming, crops: maize, beans
SPECIES : Trees -
: Shrubs -
: Grasses/forbs-

LAND ELEMENT : interfluve
MICRO TOPOGRAPHY: even
VEGETATION: Nil

POSITION: intermediate part
SLOPE : - 1 % straight
GRASSCOVER:

PARENT MATERIAL: in situ weathered
MOIST. COND: dry 0 - 097, slightly moist 097 - 180 cm
SURF.STONES: none
EROSION : moderate sheet erosion

ROCK TYPE: granite
ROCK OUTCROP: none

GEOL.UNIT: Gaborone granite
DRAINAGE : well drained
HUMAN INF: ploughing

REMARKS:

SAMPLES: A: 0 - 10 B: 12 - 30 C: 35 - 50 D: 55 - 95 E: 95 - 125 F: 125 - 155 G: 155 - 180

Ap	0 - 11 cm	Dark brown (10YR 3/3) (moist) and dark yellowish brown (10YR 4/4) (dry), sandy loam (15% clay), weak medium subangular blocky falling apart into weak fine granular structure, slightly hard, very friable, non sticky, non plastic, few very fine pores, non calcareous, common fine to medium roots, field pH: 5.5, abrupt wavy boundary.
A	11 - 33 cm	Dark brown (10YR 3/3) (moist) and dark brown (10YR 4/3) (dry), sandy loam (18% clay), weak medium to coarse subangular blocky structure, hard, very friable, non sticky, non plastic, few very fine pores, non calcareous, common fine to medium roots, field pH: 5.5, clear wavy boundary.
Bt1	33 - 51 cm	Dark brown (7.5YR 3/4) (moist) and strong brown (7.5YR 4/6) (dry), sandy clay loam (22% clay), weak coarse subangular blocky structure, hard, friable, sticky, slightly plastic, broken thin cutans on pedfaces and broken thin cutans random, few very fine pores, non calcareous, very few very fine to fine roots, field pH: 6.0, diffuse wavy boundary.
Bt2	51 - 97 cm	Dark reddish brown (5YR 3/4) (moist) and yellowish red (5YR 4/6) (dry), sandy clay loam (28% clay), weak coarse subangular blocky structure, hard, friable, sticky, slightly plastic, broken thin cutans on pedfaces and broken thin cutans random, few very fine pores, non calcareous, few fine to medium and few coarse roots, field pH: 6.0, diffuse wavy boundary.
Bt3	97 - 180 cm	Yellowish red (5YR 4/6) (moist) and yellowish red (5YR 5/6) (dry), sandy clay loam (30% clay), weak coarse subangular blocky structure, very hard, friable, sticky, slightly plastic, broken thin cutans on pedfaces and broken thin cutans random, few very fine to fine pores, non calcareous, few fine to medium roots, field pH: 6.0, abrupt smooth boundary.
Cmo	180 - 190 cm	extremely hard, cemented.

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