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I am submitting herewith a thesis written by Hans Walter Schumann entitled "Potential for Moisture Stress on Vegetation on the Cumberland Plateau of Tennessee." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

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POTENTIAL FOR MOISTURE STRESS ON VEGETATION ON THE CUMBERLAND PLATEAU OF TENNESSEE

A Thesis

Presented for the

Master of Science

Degree

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Hans Walter Schumann

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ABSTRACT

Because precipitation during the months of the growing season generally is lower than for the rest of the year and soils are mostly shallow, moisture stresses that are detrimental to plant growth are frequent.

The objective of this study was to evaluate the potential for moisture stress on vegetation for an area of the Cumberland Plateau near Crossville, Tennessee. Determining the recurrence of specific climatic moisture deficits, soil moisture deficits, and the impact of soil moisture deficits for different groupings of plants were all part of the analytical design.

In order to deal with long-term as well as short-term moisture conditions two methods were employed. A water budget model was used to analyse moisture deficits on a monthly basis. Short-term moisture conditions were evalated by determinating the probability of the occurrence of dry-day sequences of various lengths.

The study showed that moisture stress on vegetation is relatively frequent in the study area. Plants most affected are those with a limited root system or where soils are shallow, which is widespread. There is a definite trend that soil moisture depletion increases from southwest to northeast as a result of prevailing meteorologic conditions.

Temporal differences of moisture stress are marked as

well. Moisture deficits increase steadily from May to October. Moisture conditions are significantly less favorable in the last half of the growing season compared to the early half.

From a perspective of moisture supply, deep rooting crops with critical moisture sensitive stages in the early season are more suited for the study area than crops that have a shallow root system and that have moisture sensitive periods in the late part of the growing season.

Tree species such as Shortleaf pine and Loblolly pine appear best suited here because they do not have a critical late summer stress period. The study has shown that because of thin soils and low total moisture storage in most of the forest soils it is reasonable to expect trees to suffer severe moisture stresses quite frequently. Survival of tree seedlings is threatened, especially on newly replanted plots where there is no protective tree canopy to reduce transpiration rates.

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CHAPTER I

INTRODUCTION

Availability of moisture is one of the most important factors influencing plant growth and crop yield. Insufficient moisture supply leads to water stress in vegetation, which directly affects the biological functions of a plant. Results are decreased growth and reduced crop yield and crop quality.

In most climatic regions the supply of plant available water is a strongly variable factor of the environment. Even in humid regions of the mid-latitutes, droughts are frequent and severe. Therefore, to determine the potential for moisture stress on vegetation in a specific area, it is essential to assess the variability of the supply of plant available water.

The amount of water that is accessible to plants depents mainly on two factors, precipitation and storage volume of the soil. Precipitation represents the amount of moisture that is potentially available to plants. The properties of the soil determine how much of the water that has been supplied by precipitation can actually be utilized by the vegetation. The storage volume is determined by the root penetrable depth of the soil layer and the water holding capacity within the root zone.

Soil moisture and precipitation are figures that

determine the supply of water. This supply has to meet the water demand of the environment. The demand usually is expressed by the potential evapotranspiration (PE). PE represents the potential combined loss of water by evaporation from the earth's surface and transpiration by plants, assuming the availability of sufficient water.

If PE exceeds the supply of water from precipitation the moisture storage of the soil will be depleted and moisture stress may occur. It is the objective of this study to determine the frequencies and the severities of soil moisture deficits in the study area and to evaluate the potential for moisture stress on vegetation.

The study area is on the Cumberland PLateau in the vicinity of Crossville, Tennessee. It is an area were precipitation during the months of the growing season generally is lower than for the rest of the year. Soils in the area usually are shallow to moderately deep. These conditions imply frequent moisture stress for plants.

Although irrigation is practiced in some larger farming operations (e.g. Cumberland Mountain Farms, University of Tennessee Experiment Station), it is questionable whether the area of irrigated land can be further expanded. Studies (Wilson, 1965; TVA, 1968) have shown that water resources are very limited during the period that is critical for plant growth.

Thus, soil storage is the only source of moisture for

plants that most farmers have to rely on. An evaluation of the resources of soil moisture therefore is needed to determine the potential and the risk for agriculture in the study area.

Furthermore, the original forest of the area was predominantly hardwoods but commercial reforestation is dominated by softwood species, especially pines. This raises the question whether the area is suited for commercial softwood production, particularily whether the selected species are appropriate, considering the potential droughtiness during the growing season.

In this study, the recurrence of specific climatic moisture deficits and resulting soil moisture deficits will be analysed. Given degrees of soil moisture depletion can be related to specific plant responses. Therefore it will be possible to assess quantitatively the probability of the occurrence of moisture stress and its effects on different kinds of vegetation.

Review of the Literature

A wide variety of studies exist that are concerned in some way with the problem of moisture stress on vegetation, or as it is more often referred to, agricultural drought.

Many of these studies focus on the determination of potential and actual evapotranspiration. Measurement of evapotranspiration is very problematic and the results of

many lysimeter measurements are questionable in their to theoretical methods for calculating evaporation. Several formulae have been developed but the discussion on their applicability and their accuracy is far from settled.

The two formulae that are most commonly referred to are those by Thornthwaite (1948) and Penman (1948). Thornthwaite's formula was derived from empirical data of the eastern United States. The formula consists of only four factors, an empirical constant, a heat index, the mean temperature of the study period, and the latitute of the station as a surrogate of the value for solar radiation. The empirical constant and the heat indices are readily available in tables that were published by Thornthwaite and Mather (1957), and information on mean temperatures is available for most parts of the world.

The availability of usable data is probably the main reasons for the widespread application of the Thornthwaite model, despite of its known weaknesses. When applied to data from outside the eastern United States or comparable climatic regions, the model may not generate satisfactory values, as Uhlig (1954 and Dammann (1965) have demonstrated for Central Europe. In the eastern United States ,however, the formula produces appropriate results. In a study dealing with agricultural drought in the southeastern United States, Safley (1974) found evapotranspiration values derived by the Thornthwaite method to be more appropriate

than those calculated by the Penman formula. The greater array of variables needed to use the Penman formula also limits its applicability even though some investigators belief it to be the better empirical formula (Chang, 1965).

A water budget approach developed by Thornthwaite and Mather (1955) is considered appropriate and used in this study. Data for the potential evapotranspiration, precipitation, and the waterholding capacities of the soils are available and the model can be used to assess soil moisture status on a daily or long-term basis.

A method to define agricultural drought on the basis of soil moisture conditions and resultant plant behaviour was developed by Van Bavel (1953). Using the Thornthwaite method he calculated soil moisture depletion and determined the frequency of drought days. Van Bavel defined drought days as days were soil moisture is depleted to a degree that causes appreciable reduction of the productive processes of the vegetation.

Palmer (1965) introduced a meteorological drought index that can also be applied to evaluate agricultural droughts Palmer, 1968). Basically, the method evaluates moisture conditions as deviations from long-time mean moisture conditions. With this analysis various degrees of drought severity can be assessed.

Hershfield et al. (1973) attempted to give some measure of agricultural drought by calculating the

probability of dry day sequences. Characteristics of the soil were not considerd in their study.

To be able to relate specific moisture conditions to corresponding plant responses, it is necessary to know the plant-water relationships for different species. Studies on these relationships are manifold and have been done for many of the common crop and tree species.

Comprehensive studies on crop-water relations have been published by Chang (1977), Kozlowski (1968), and Taere and Peet (1983). Important studies summarizing the relation of water and tree growth are provided by Kozlowski (1976) and Mitscherlich (1970). The findings of these studies are the basis for the evaluation of droughtiness on crop and forest production discussed later in this study.

CHAPTER II

THE STUDY AREA

The study area is defined by the watershed of the Obed River upstream of the gaging station located two kilometers upstream from its junction with the Emory River (Figure 1). It covers most of Cumberland County and parts of Bledsoe. Fentress and Morgan Counties and totals 1342 square kilometers.

Topography

The study area lies almost entirely within the Cumberland Plateau. The western two-thirds of the study area have the most characteristic properties of the plateau. Elevations range from 500 to 600 meters. The land surface is flat to gently rolling, with steep slopes only along the drainageways. The larger rivers have cut valleys 30 to 100 meters below the plateau surface.

The eastern section of the study area. belonging to the Crab Orchard Mountains. shows predominantly steep slopes and elevations that reach almost 1000 meters. This part of the study area is more strongly dissected than the western part and exhibits distinct mountainous physiographic characteristics.

About 28% of the study area consists of flat land with slopes of less than 5% and about 30% has slopes of 5 to 9%.

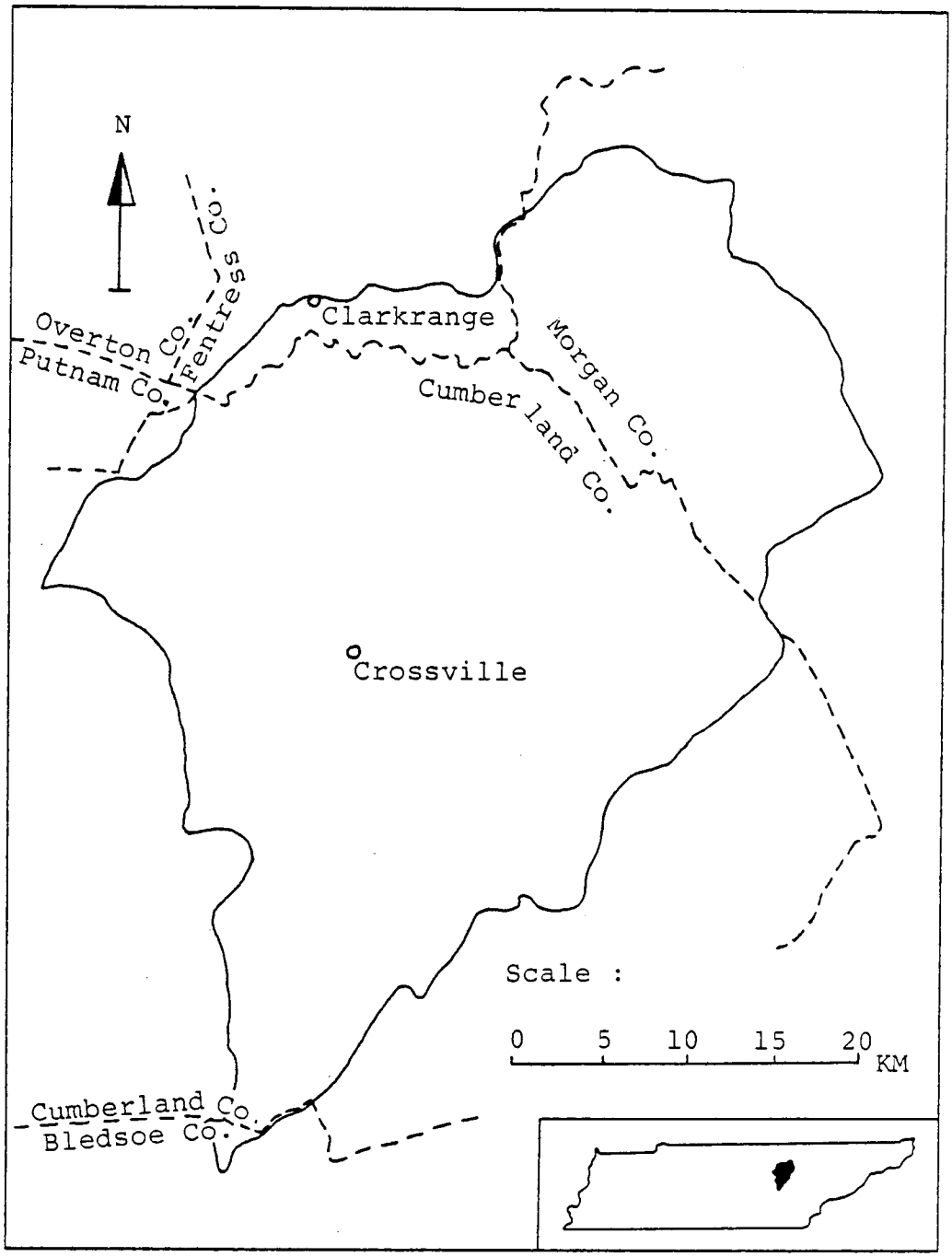

Figure 1. The study area.

steep slopes (more than 30%) occupying 5% of the study area. Figure 2 shows the spatial distribution of four slope catagories. Those categories were chosen to represent limitations to different forms of land use. As a rule crop agriculture should not be practiced on slopes of more than 5% if erosion is to be minimized. Slopes with gradients of up to 9% are feasable for use as pasture. On slopes of more than 9% agriculture should not be practiced(Bell et al.,1981).

Drainage

The runoff regime of the Obed watershed shows a very distinct seasonality. Highest runoffs are recorded during the winter and spring months, while late summer and early fall are a period of low-flow. The differences in discharge of the two runoff seasons are striking. While peak values in winter and spring are extreme in relation to the size of the watershed, low-flow discharges are very small and runoff can cease in the smaller tributaries for more than a month. This, and the fact that the lag time between meteorologic events and the corresponding runoff responses is very short, indicates the absense of large groundwater and soil water storage capacities.

Precipitation

Average annual precipitation for the 30-year period from 1950 to 1979, ranges from 1291 to 1443 mm, with

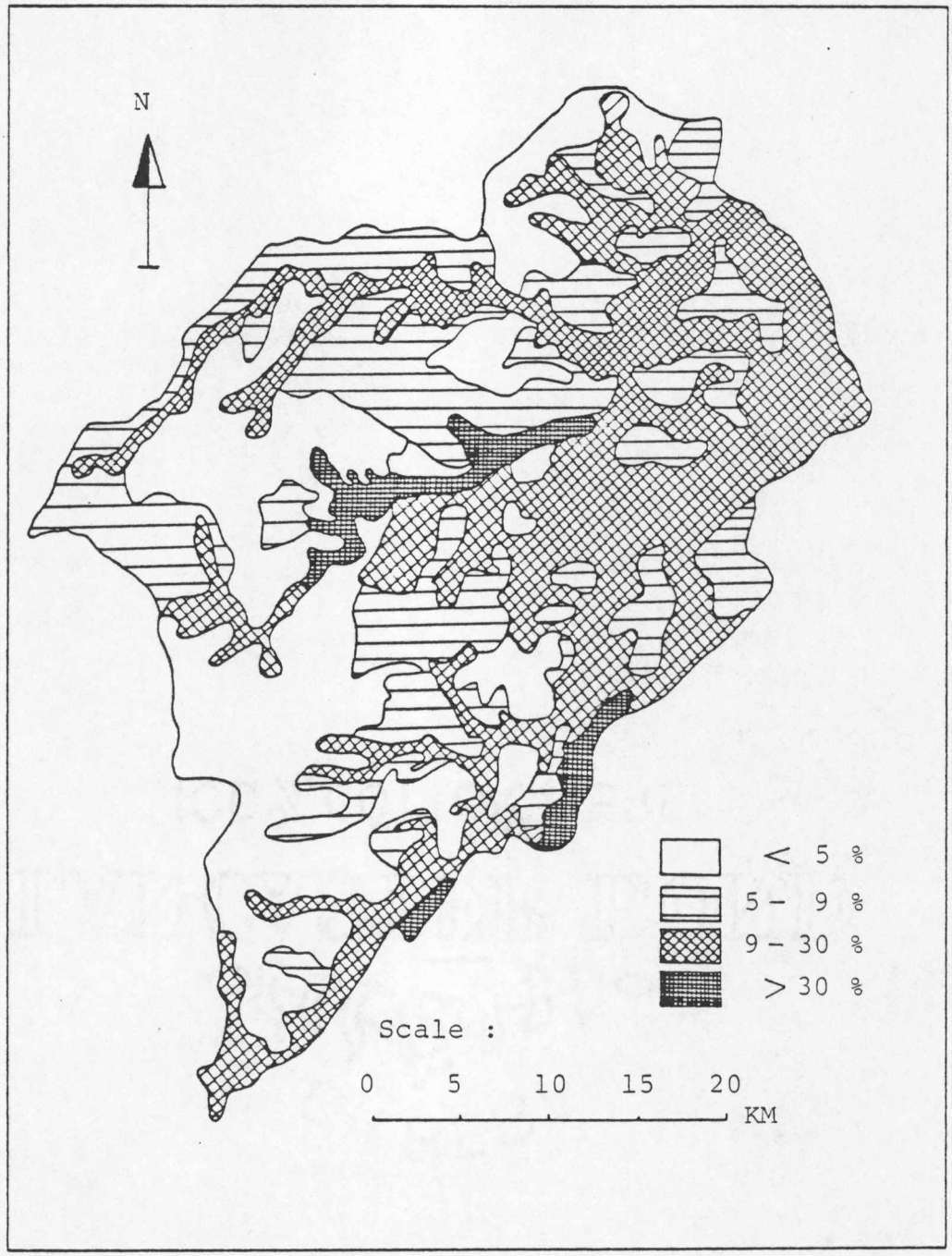

Figure 2. Distribution of slopes.

decreasing values from southwest to northeast. Because of the differences in the spatial distribution of the precipitation, the study area can be divided into a wetter part in the southwest and a drier part in the northeast. This division is based on the evaluation of the records of eight stations within, and two close to, the study area. Figure 3 shows the areal extent of each of the two subdivision of the study area. The dividing line between the two subdivisions was drawn along the line of the steepest gradient of the isohyets. Data for the Crossville Experiment Station represent subdivision I, and those of the Clarkrange station represent subdivision II.

The annual distribution of rainfall shows similar patterns for both stations. The winter and early spring months are the period of heaviest precipitation, averaging more than 140 mm per month in the southwestern part and more than 120 mm per month in the northeastern part of the study area. Late spring and late summer/early fall show lower precipitation values, with least rainfall occurring in October. The two periods of lower precipitation are separated by a peak value of rainfall that generall occurs in July.

Studies by Safley (1974) on the probability of dry and wet days in Crossville indicate that the greater precipitation in July results from higher intensity of rainfall rather than increased number of rainy days.

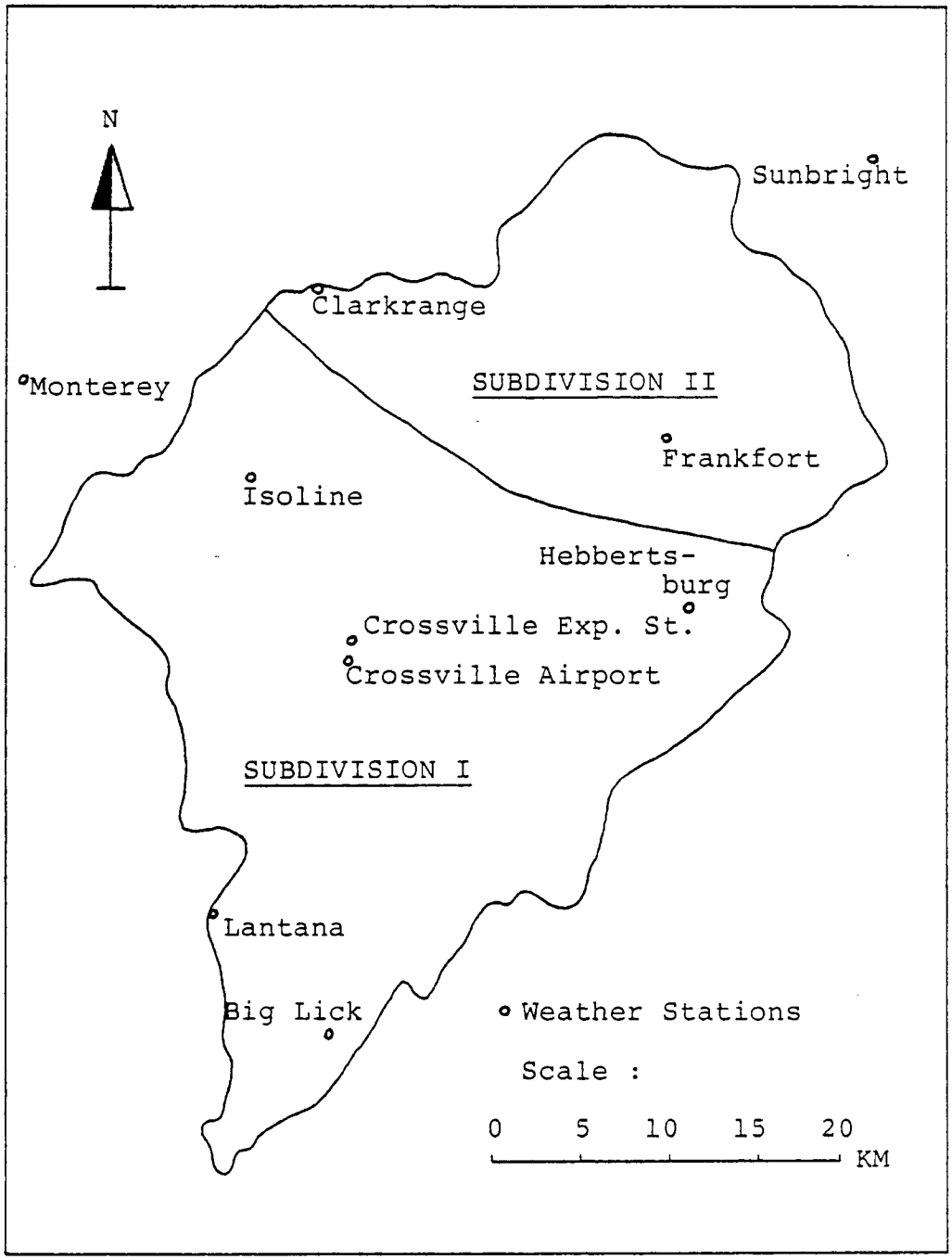

Figure 3. Subdivisions of the study area.

rainfall rather than increased number of rainy days. Because the pattern of precipitation in both subdivisions is very similar. it can be assumed that this is true for the entire study area (Figures 4 and 5).

The year to year variations of total annual precipitation are similar for both stations. The maxima and minima deviated approximately 30% from the mean value. ranging from 1015 to 1921 mm in Crossville and from 918 to 1690 mm in Clarkrange. The variations of the total rainfall during the growing season (May through October). however. differ significantly for both stations.

In Crossville the total amount of rainfall during the growing season on the average is 624 mm but the maximum was 1139 and the minimum 314 mm. These values represent deviations of 83% and 50%. respectively. In Clarkrange. deviations from the average were much smaller. The maximum of 1139 mm deviated 49% from the mean value of 571 mm. while the minimum of 380 mm represents a deviation of only 33% from the mean.

Temperature and PE

Temperature data for the study area are available for only one station (Crossville Experiment Station). Therefore temperature and corresponding PE-values are based solely on the records of the Crossville Experiment Station. It is assumed in this study that these data are representative for

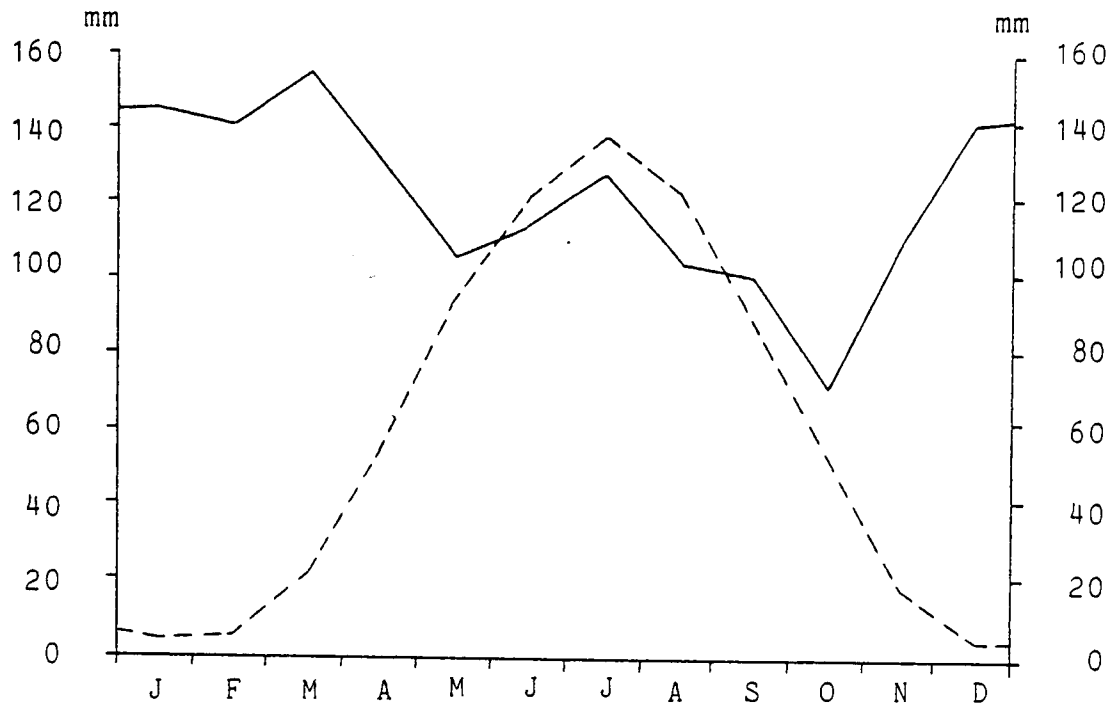

Figure 4. Average monthly precipitation and potential evapotranspiration in Crossville.

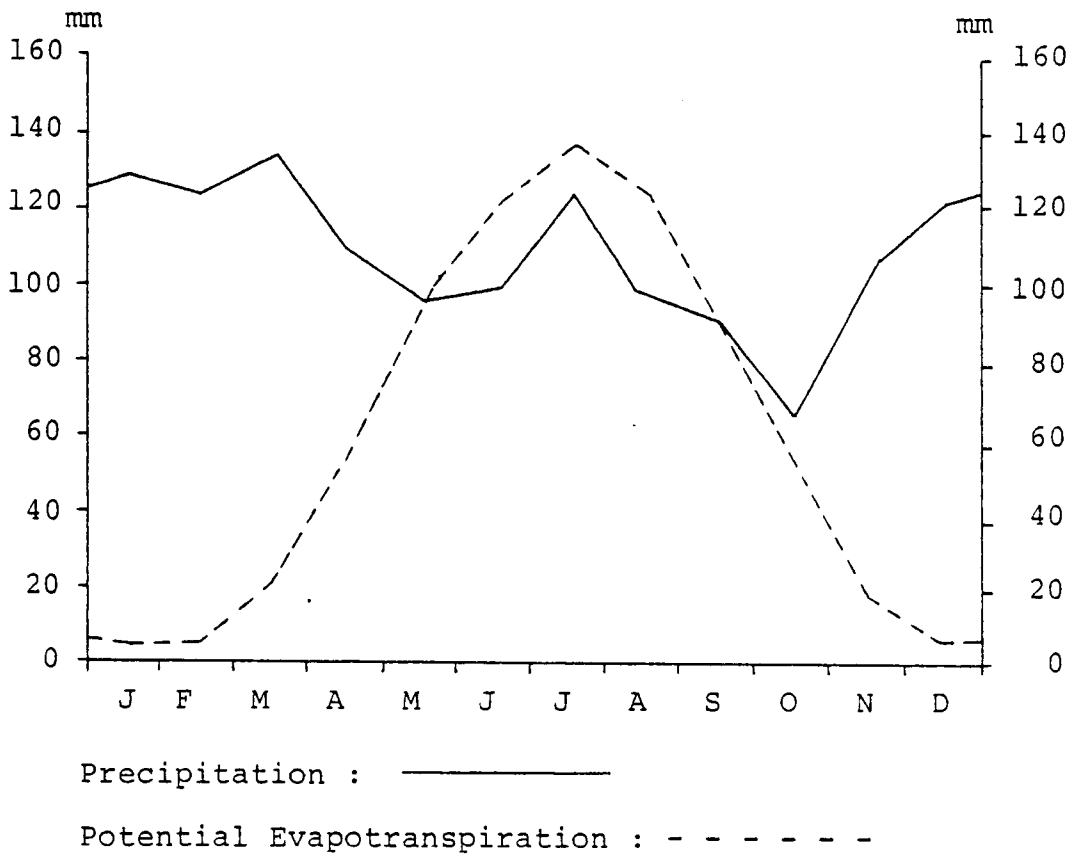

Figure 5. Average monthly precipitation and potential evapotranspiration in Clarkrange.

differences accoording to elevation. The variations are not expected to be significant, however.

For the period from 1950 to 1979, the records show a mean annul temperature of 12.4°C. The annual averages vary only slightly, from 11.1°C to 13.3°C. The mean monthly temperatures generally exceed 20°C in the months of June, July, and August. The frost-free season lasts approximately 180 days, although killing frost can occur as late as mid-May and as early as late September. The period from May through October can be considered the prime growing season. In each of those months the mean monthly temperature exceeded 7°C in every year for the period of record used here.

PE values, derived by the Thornthwaite method (Thornthwaite and Mather, 1957), totaled 728 mm for the average year. The mean total for the months of the growing season was 620 mm, with all months except October having PE values close to or above 100 mm. Average PE for October was 52 mm. Thus daily PE was roughly 3.0 mm in May and September, 4.0 mm in June and August, 4.5 mm in July, and only 1.7 mm in October.

In Crossville, PE values for the growing season equal the amount of precipitation for the same period. In Clarkrange, PE is some 50 mm higher than the rainfall received. Average PE values exceed the average precipitation in Crossville in the months of June, July, and

August, while in Clarkrange PE exceeded precipitation also in May and equaled it in September.

Because of the strong relationship of temperature and PE, the pattern of PE is very similar to that of temperature. This means that year to year variations in PE are not very great. Accordingly, moisture deficits during the growing season are most likely a result of subnormal precipitation rather than increased temperature and corresponding PE values.

The spatial variations of PE that occur as results of differences in slope and aspect are very difficult to quantify. PE values on southfacing slopes will be higher than those on northfacing ones, because of longer insolation time and higher radiation intensity. The effects on soil development and vegetation cover can be very marked in locally limited ares, but are not considered in this study.

Soils

The predominant soil types of the study area are Crossville Loam, Hartsells Fine Sandy Loam, and Muskingum Fine Sandy Loam. They cover approximately 80 to 90% of the entire area. The remaining 10 to 20% consist of some other types of loamy soils, ranging from light textured sandy loam to heavy textured silty clay loam.

Representative figures for the water holding capacities (WHCs) of these soils are given by T.J. Longwell (1963) in

the Bulletin of the Tennessee Experiment Station. According to this report the following connections between texture of typical Plateau soils (values for the Crossville and Hartsells soil groups were taken and averaged) and their WHCs can be expected :

sandy loam	131 mm/m WHC
loam	192 mm/m WHC
fine sandy loam	229 mm/m WHC
very fine sandy loam	275 mm/m WHC

To assure easier handling in the calculations that will follow, four hypothetical soil types were assumed, with the following characteristics in respect to their WHCs :

Soil A	120 mm/m WHC
Soil B	150 mm/m WHC
Soil C	200 mm/m WHC
Soil D	250 mm/m WHC

The soils A, C, and D very closely represent the actual soil types of sandy loam, fine sandy loam, and very fine sandy loam, respectively.

Although soils in the study area show relatively uniform properties with respect to their texture, the agricultural potential of the soils varies greatly. This is primarily due to the differences in depth and stone content. Those characteristics are closely related to the gradient of

slope. In the flat and gently sloping areas (less than 5 percent slope) soils generally reach a depth of 90 to 100 cm, but only rarely do they exceed this limit. Moderately steep slopes (5 to 9 percent) are covered with soils, ranging from 60 to 90 cm in thickness, while on the steep slopes (more than 9 percent) soils are shallow and rarely exceed a depth of 60 cm. The content of coarse material, larger than the sand fraction, relates best to the gradient of slopes. On steep terrain high content of loose stones and numerous bedrock outcrops are fairly common.

Tough clayey B-horizons pose a problem to agricultural use only in very small areas. They are primarily limited to silty clay loams (sCL) and silt loams (SL) of the soil groups Dunning (sCL), Emory (SL), Hartsells (SL), Talbot (SL), and Wolftever (SL), each of these soils comprising less than one percent of the study area.

The influence of aspect on soil development and soil properties was described by Knight (1979) for a comparable area in Campbell County, Tennessee. Soils on northfacing slopes were characterized by a better developed and thicker A-horizon, with relatively high organic matter content. Southfacing slopes showed a thinner A-horizon but the development of the B-horizon, accompanied with some clay accumulation, was stronger than on the north aspect.

Agriculture

The 1978 census of agriculture indicates that cropland and pasture land account for only 14 percent of the total land area in Cumberland County and for 7 percent in Morgan County. The portion of cropland and pastureland in the study area was estimated to be roughly 10 percent, or 130 square kilometers.

The main agricultural commodities by acreage were hay crops, corn, vegetables, soybeans, and to a lesser extent wheat. Of the orchard products only apples have some importance. Vegetables account for the highest market value of all crops sold.

Only the Cumberland Mountain Farms irrigates extensively, with vegetables being the primary products. The Cumberland Experiment Station of the University of Tennessee practices irrigation largely on an experimental basis.

Forestry

As of 1969 approximately 75 percent of the total study area was in forests of which 90 percent was considered comercial forestland. This ammounts to a total of 70 percent commercial forest land of the entire study area, or 900 square kilometers.

Hardwood species dominated by a wide margin over softwoods. They accounted for more than 75 percent of all

trees. Most important species were Red and White Oaks and Hichory. There is a trend, however, to convert hardwood stands into pine on lands that are reforested. Shortleaf and Virginia Pine are the preferred softwood species but Loblolly, White and Yellow Pine are planted as well.

According to TVA (1969) the productivity of the commercial forests in the study area was less than 50 percent of its estimated potential.

CHAPTER III

MOISTURE STRESS SUSCEPTIBILITY OF VEGETATION

Moisture stress in plants is not a simple function of the meteorological supply of water but varies with the volume of soil moisture storage, the depth and volume of plant roots, species tolerance to moisture stress, and the seasonality of critical stress susceptibility in plants. A review of the non-meteorological factors is now in order as a guide in designing the analysis of occurrences of meteorological dryness.

Rooting Depth

Rooting depth probably is one of the most obvious factors influencing the capacity of a plant to adapt to meteorological drought conditions. There is a strong relationship between the depth of the root zone and the amount of available soil moisture. Deep-rooted plants can draw moisture from a larger volume of soil than shallow-rooted plants, which in turn means that they can endure longer periods of insufficient precipitation. Based on the work of Thornthwaite and Mather (1957) three categories of crops will be distinguished in this study, each of those categories characterized by an averaged root depth for a given soil condition.

Shallow-rooted crops are those with a root zone varying

from 25 cm to 62 cm in depth. Crops in this category are mainly vegetables. The second category, moderately deep-rooted crops, includes such plants as corn, cereal grains and tobacco. Depending on soil conditions, the rooting depth varies from 50 cm to 100cm. Finally the deep-rooting crops are mainly comprised of alfalfa, pastures, and shrubs. Extreme values for depth of root zone are 67 cm and 125 cm, respectively. The general values for depths of roots by soil texture class for different vegetation and the resulting values of available soil moisture are shown in Table 1. Variations of rooting depth of crops of the same category result from differences in the penetrability of the soils. The penetrability is primarily related to the soil texture.

For mature trees, forest as well as orchard, it can be assumed that the root zone equals the existing soil depth. Root extension by trees also varies with soil texture and, like crops, there are depth limits inherent to the species, but the soil conditions in the study area rarely provide soil depths great enough to equal or exceed the potential rooting depth of most trees.

An important factor that has to be considered is that the density of the root system of a plant is not uniform but varies with depth. As a general rule, it can be expected that within the uppermost third of the root zone roughly half of the root volume is concentrated. On the other hand,

Table 1. Provisional water holding capacities with different combinations of soil and vegetation.

Soil Type	Available Water (mm/m)	Root Zone (cm)	Soil Moisture in Root Zone (mm)
Shallow Rooted Crops			
Fine Sand	120	50	60
Fine Sandy Loam	150	50	75
Silt Loam	200	62	125
Clay Loam	250	40	100
Moderately Deep Rooted Crops			
Fine Sand	120	85	100
Fine Sandy Loam	150	100	150
Silt Loam	200	100	200
Clay Loam	250	80	200
Deep Rooted Crops			
Fine Sand	120	100	120
Fine Sandy Loam	150	100	150
Silt Loam	200	125	250
Clay Loam	250	100	250

Source: Thornthwaite C.W., and Mather J.R. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publications in Climatology Drexel Institute of Technology. 10: 309.

plants react to dry soil conditions by extending the deeper parts of their root network. An evaluation, specially the quantitative evaluation of these two factors is very complex and will not be dealt with in this study. Moreover , it can be expected that the positive effects of active plant response to unfavorable soil moisture conditions cannot fully compensate for the negative effects of the uneven distribution of the root mass. Therefore, the findings of this study may be somewhat to optimistic, which should be kept in mind when interpreting the results of this investigation. One should allow a margin error to compensate for the uncertainties of this complex phenomenon.

It should also be noted that all values for depth of root zone are generalizations and refer to plants in a mature stage of root development. Plant in an embryonic or seedling stage have a more limited root system and may have less tolerance to moisture stresses than mature plants. For annual field crops it can take a few weeks or months to reach full root development, for trees it takes several years. This should be realized when comparing the the demand and the supply of moisture for a given crop in the early growing season. Tree seedlings should be considered separately from mature plants of the same species. Depending on the age of a tree seedling it can be put in the same categories as shallow, moderately-deep, and deep-rooted crops respectively.

Seasonal Variations of Water Demand

Besides temporal variations in water stress response related to the stage of development of the root system, there are seasonal variations that are influenced by changes in the physiologic activities of a plant. Most crops have "moisture sensitive periods" (Chang, 1977) during which a water deficit depresses the economic yield much more than in other periods. Table 2 gives some information on moisture sensitive periods for several crops and the effect of moisture shortage during those stages. The table shows that the critical moisture sensitive periods for most crops last only a few weeks. The figures further suggest that trees, too, have short-term moisture sensitive stages. These are critical in that they influence reproductive functions and fruit development, the latter being of greatest importance for orchard trees.

Forest trees also have certain short-term moisture sensitive stages. In forest management, however, the main emphasis is on wood production, rather than fruit development. Thus, it seems more important to look on long-term moisture conditions and to distinguish between moisture supply in the early and in the late growing season. Such a distinction is reasonable because the wood produced in the early season differs substantially in its properties from wood produced in the late season. Latewood has a

Table 2. Critical moisture sensitive periods for selected crops.

Crop		
Beans	during flowering and pod development	badly crooked or malformed pods; reduction of fibrous content of beans
Cherries and Peaches	period of rapid growth prior to maturity	canned peaches are tough and leathery in texture
Corn	period of silking and ear growth	significantly decreased yield; decreased number of large marketable ear for canning and freezing
Potatoes	after formation of tubers	substantial decrease in yield; reduced specific gravity is likely
Soybeans	period of major vegetative growth and blooming	lower protein content; slightly higher oil content
Wheat	during the period of heading and filling	significantly decreased yield

Sources: Chang, J.H. 1965. Climate and agriculture. Aldine Publishing Co., Chicago. 304p.
Teare, I.D. and Peet, M.M. 1983. Crop-water relations. Wiley, New York. 547p.

higher specific gravity and density than earlywood and thus, better mechanical characteristics, while earlywood accounts for the greater volume of the radial growth. It is not possible to give a general statement on the effect of water shortage on the earlywood-latewood ratio. The effects vary from species to species and are often contrary for softwoods and hardwoods.

Haygreen and Bowyer (1982) state that increased growth rate in hardwoods tend to increase wood density, while for softwoods there appears to be the opposite relationship. However, in the same study the authors mention that such rules of thumb have to be used with caution because thay do not always apply for all species and, additionally, water supply is not in all cases the only factor influencing growth rate. Nevertheless, it is shown that moisture conditions in the early season have different impacts on radial growth and wood properties than those in the late season.

A distinction between early and late season is further suggested by the findings of Kozlowski (1976) and Chang (1977). Both state that shoot growth in several species can be looked upon as a two year process. When buds are formed in late summer but the expansion of the bud occurs in the following spring , moisture conditions of the one year will have a carry over effect influencing growth rate in the following year. According to Kozlowski (1976), this process

is true for the majority of temperate zone species. However, it should be noted that some pine species are exceptions of this rule (Pinus taeda - Loblolly pine, Pinus echinata - Shortleaf pine), while other pines such as Pinus resinosa (Red pine), Pinus strobus (Eastern White pine) and Pinus monticola (Western White pine) follow the rule.

This example shows the complexity of the problem of tree growth-water relations. Generally,it can be said that moisture conditions have a direct effect on quality and quantity of wood production. The review of the literature has also shown that there are important differences in wood development between the early and the late growing season and it is therefore approriate to look separately on those two periods of growth.

Species Specific Drought Tolerance

In a biologic sense drought tolerance could be defined by the percentage of a plant's water content that has to be lost to cause permanent wilting. Factors that determine the time span that is required to reach this critical value of water loss are, among others, the water use efficiency of a species and the total amount of water stored in the plant.

Data on these factors, however, are very difficult to obtain or to evaluate collectively. Also, to choose the permanent wilting point as determinant for drought tolerance does not consider economic realities. In commercial crop

production, a small water stress may cause substantial yield reduction. Therefore, for the purpose of this study, the term "specific drought tolerance" has been given an economic variable in addition to the biologic one, so that one could define drought tolerance as the water stress that can be accepted from an economic point of view because its impact on production is acceptable.

As a general rule annual field crops have a low drought tolerance because small water shortages lead to decreases in yield that can be economically costly, even if the shortage does not mean a threat to the survival of the plant itself. Trees on the other hand have a high drought tolerance in a biological as well as an economical sense. An indication of the biological drought tolerance is given by Kozlowski's (1968) definition of a severe soil water deficit for trees: "available [soil] water exhausted and remaining so for at least one month." Additionally, from an economic perspective reduced growth caused by moisture stress is more acceptable for trees because of their perennial nature. There is a chance that subnormal growth in a dry year can be compensated for, to some extent, by greater than normal growth in years with above average climatic conditions. This is of course also true for field crops but management goals and the time periods between investment and profit are quite different in agriculture and forestry. Another factor of course is that very often in areas where wood is produced

there is no other possible land use alternative because of unfavorable environmental conditions.

Summary

Summarizing one can say that, according to the definition of "specific drought tolerance" as used in this study, a very generalized distinction between two groups of plants can be made. The first group are those plants with a relatively high tolerance and comprise all forest trees. The second group is characterized by a low drought tolerance. To this group belong all kinds of field crops. Orchard trees, when considering both economic as well as biologic factors, have a low drought tolerance because fruit production is the main emphasis rather than wood production. Thus they can be included in the same category as field crops.

Within the group of plants with high drought tolerance, two subgroups can be distinguished. The first sub group is comprised of trees that are more tolerant to moisture stress in the early season. Trees of the second su bgroup show stronger resistence to droughts in the late growing season.

For all plants the depth and the volume of the roots are the main determinants of the amount of potentially available moisture. Characteristics of the root systems show considerable differences for different kinds of vegetation. In addition, the potential root depth is often

limited by the existing soil depth in a specific area.

All three factors, root depth, seasonal variation of water demand, and specific drought tolerance, have to be considered when deciding on the best suited methods for evaluating water stress potentials in a given area under certain environmental conditions.

CHAPTER IV

METHODS

The analysis of moisture stress, its magnitute, seasonality and frequency of occurence, is based on water budgeting proceedures. Meteorological dryness is analysed first, followed by application of these data to the assessment of soil moisture deficits and moisture stresses on specific groupings of plants.

The investigation on longer time periods was based on monthly data. Thus statements on moisture conditions could be made for single months and for longer periods, namely the entire growing season or the first or second half of the growing season. The significance of each of these time spans was mentioned earlier.

Short-term moisture conditions were studied by focussing on periods varying in length from one to fifteen days. The fifteen day threshold was chosen because it is expected that sequences of more than fifteen consecutive dry days occur only very rarely and that dry spells of a significant recurrence interval are shorter than fifteen days.

To assess the potential of moisture stress, it is generally necessary to determine the frequency of specific long-term and short-term moisture conditions.

Monthly P-PE

The method chosen to assess long-term moisture stress situations is a monthly water budget calculation. The first step of this assessment is to evaluate the meteorological moisture conditions for each month of the 30-year observation period. Values for P and PE were compared and the deficits were calculated. Besides the deficits that originated in a given months, the cumulative deficits were also determined. Special emphasis was given to the months May through October. This time period roughly coincides with the prime growing season and, additionally, the climatic data for the rest of the year indicated that all in the remaining months it is highly unlikely for PE to exceed the amount of precipitation at other times.

From the results of the water budget calculations it was then possible to assess the frequencies and the severities of soil moisture deficits for each month of the growing season. This was done for the deficits originating in a given month as well as for the accumulated deficits. The assessment gave information on how often meteorologic moisture shortages of specific degrees occurred in each month.

To give a measure on the impact of meteorologic moisture deficits on plants, it was necessary to combine information on climatic conditions with information on soil texture and depth. Obviously, the moisture storage capacity

of a soil determines whether a given meteorologic moisture shortage will deplete the water available to plants to a critical limit or not.

The evaluation of soil moisture depletion was done for the years with the first, third, and sixth highest water deficits in the entire growing season, in the early growing season (May through July) and in the late growing season (August through October), respectively. The years chosen roughly erpresent deficits with a recurrence interval of 30, 10. and 5 years , respectively. The 30-year interval, which at the same time was the highest deficit of the study period, was selected to test whether there were any climatic conditions that, under selected soil moisture storage levels, could have led to irreversable damage or fatal dehydration of trees. The remaining two examples should give information on how often and how severely tree growth was influenced by drought conditions. The 10 and 5-year intervals were thought to be periods of interest from an economic point of view of forest management.

The three sample years were determined by the sum of the deficits of each month of the period under investigation, rather than by the highest cumulative deficit at the end of a period. When looking at the entire growing period, for example, an extremely wet September could outbalance severe deficits of the previous months and thus

hide the fact that soil moisture was strongly depleted throughout most of the growing season.

Soil Moisture Analysis

To analyse the impact of specific meteorologic moisture deficits on the moisture status of the soil and on resulting plant response, the water budgeting approach by Thornthwaite (1957) was used. The water budgets were calculated for seven different types of soil moisture storage capacities. The storage capacities represent plant available WHCs within the root zone for each of the seven cases. The selection of the different values of WHCs was based on the combinations of soil texture and root depth that were previously referred to in Table 1 (page 24). WHCs of 60mm, 75mm, 100mm, 125mm, 150mm, 200mm, and 250mm were considered. Using soil moisture retention tables (Thornthwaite and Mather, 1957) meteorologic moisture deficits were then transferred into corresponding soil moisture depletion values for each of these soil conditions.

It is assumed that moisture stress occurs when soil moisture is depleted to a specific degree. The literature on plant-water relations (Kozlovski, 1968; Mitscherlich, 1970; Chang, 1977; Teare and Peet, 1983) suggests that appreciable reduction in plant production occurs when the content of plant available water of the soil has been depleted to at least half of its potential. In this analysis the severity of plant stress is expressed by

different degrees of soil moisture depletion. According to appendix A three degrees of soil moisture depletion are distinguished. A moderate depletion is referred to when less than half of the original soil moisture is retained. A severe depletion is characterized by a moisture retention of less than one third, and if less than 10 percent of the original moisture is retained the soil is considered empty (total depletion).

Dry-Days Sequences

The assessment of the occurence of dry-day sequences was done to give information on moisture conditions that are shorter than one month. These periods could not be considered in the water budget analysis that was based on monthly data. However, short-term moisture stress conditions of one or two weeks duration are significant for young crops and tre seedlings as the discussion in Chapter III has shown.

The calculation of sequences of dry days employed probability values developed by Safley (1974) for different stations in Tennessee. These probabilities were applied to data for Crossville (University of Tennessee Experiment Station) since data for other stations within the study area were not available. Safley gives information on the probability (in percent) that given days are dry and the probability that days following dry days will be dry. The

probability values of Safley are weekly averaged for the months of April through November. By multiplying the data of n days a probability figure for a dry day sequence of n days can be obtained. Although the values for n cannot be infinite, it is reasonable that the calculation for sequences of up to fifteen days is realistic.

Dry days were defined as days with a precipitation that does not exceed the average daily PE of the corresponding month. Two categories of dry days had to be distinguished; "absolutely dry days" that did not receive more than a trace of rain and "relatively dry days" that received more than a trace but less than the corresponding PE-value. This distinction was necessary because "relatively dry days" had to be processed separately in order to assess to average amount of rainfall that these days receive.

Information on the frequency of absolutely and relatively dry days then could be combined to an overall frequency of dry days, which were all days that received less precipitation than the corresponding daily PE. Considering the average daily precipitation that occurred during relatively dry days the total P-PE for specific sequences could be established.

The impact of specific dry day sequences on soil moisture status and plant production was analysed by the water budget method. It is assumed that soil moisture storage is full at the beginning of a dry day sequence. The

accumulated P-PE of a given dry day sequence determined the soil moisture depletion at the end of a particular dry day sequence. To indicate the impact on plant productivity the same terminology was used that was introduced in the analysis of the monthly water budgets (moderate, severe, and total depletion; page 37).

CHAPTER V

ANALYSIS OF MOISTURE STRESS

Long-Term Meteorologic Moisture Conditions

The results of the monthly meteorologic water budgets are graphically displayed in Figures 6, 7, 8, and 9. Figures 6 and 7 show the individual monthly meteorologic moisture deficits for May through October, for Crossville and for Clarkrange, respectively, whereas Figures 8 and 9 show the progressive accumulative deficits over these months for both stations. The cumulative data allow the determination of the frequencies of specific moisture deficits.

Simple Monthly P-PE : Figures 6 and 7 show that deficits for each succesive month from May through August increase but drop for September and October when they reach values similar to those in May. These deficits are simply P-PE for each month and do not consider the carry-over deficits from preceeding months. This trend as well as actual values were very similar for both stations. In Crossville, a deficit of 50 mm or more, which depletes the moisture of the predominant soils to about 50%, occurred with frequencies of 23 percent in July and 43 percent in August. These frequencies represent average recurrences of roughly 3.7 years and 2.3 years, respectively. For all

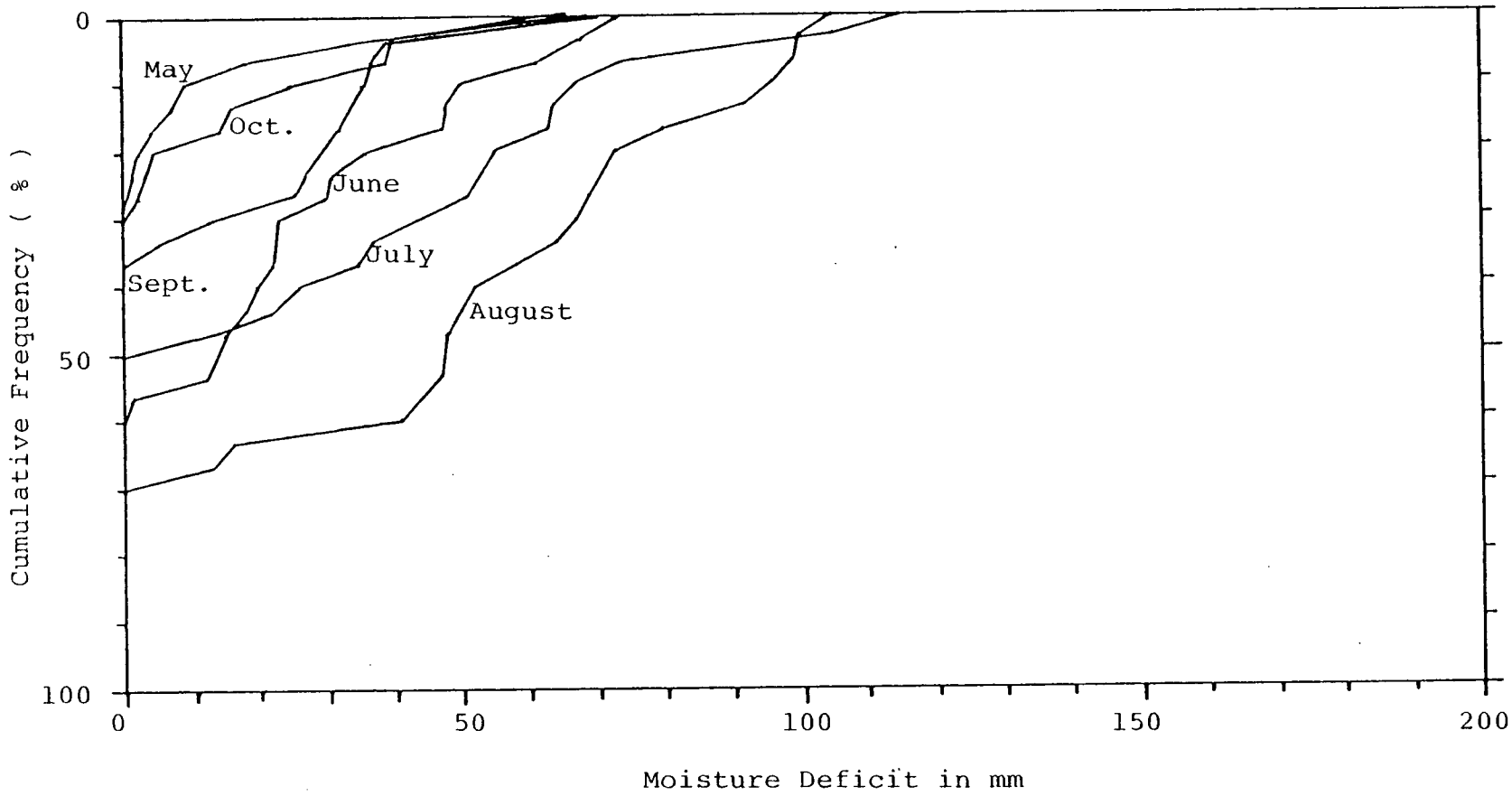

Figure 6. Moisture deficits for the months of May through October. Crossville, period of record: 1950 - 1979.

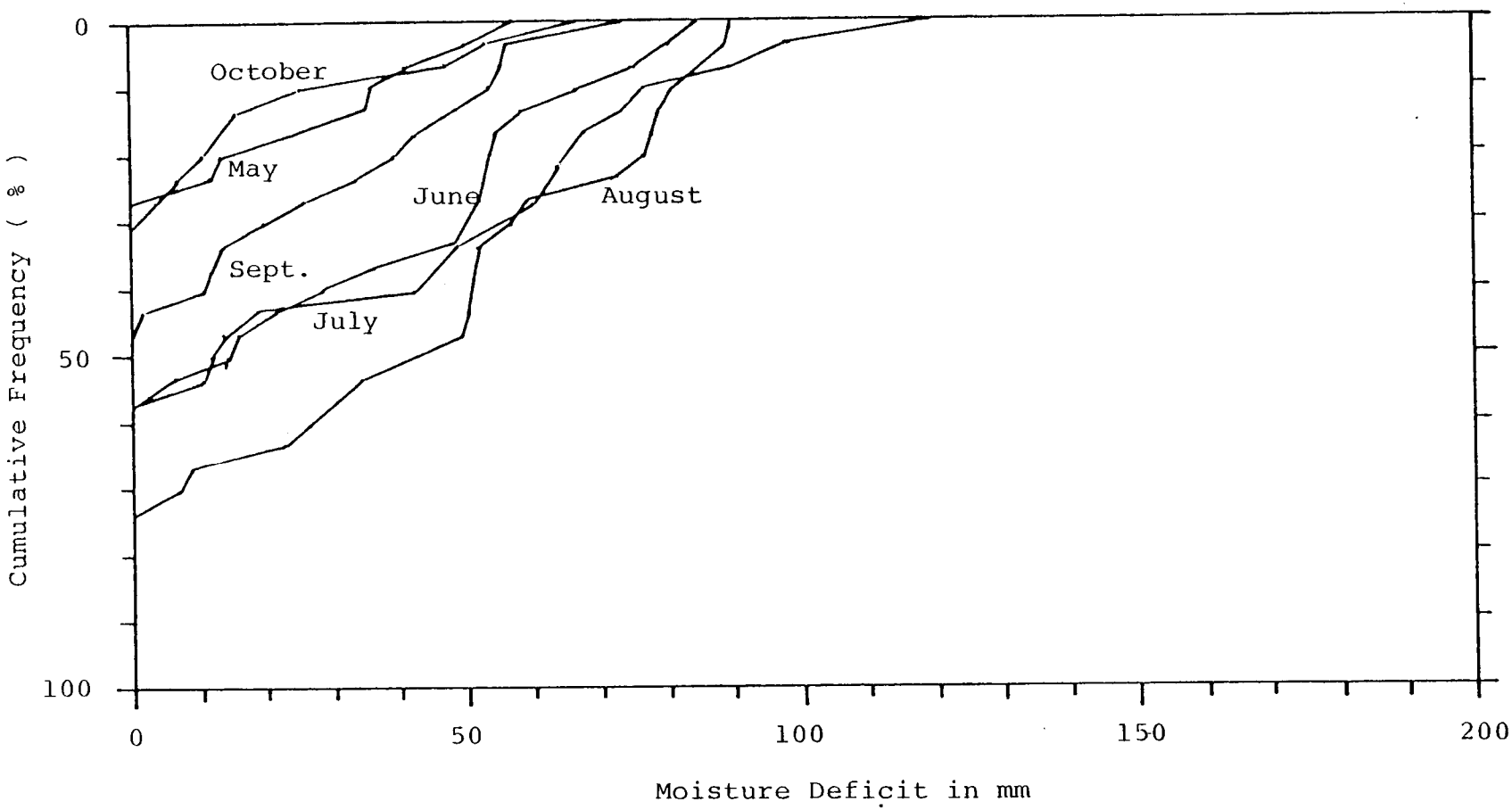

Figure 7. Moisture deficits for the months of May through October. Clarkrange, period of record: 1950 - 1979.

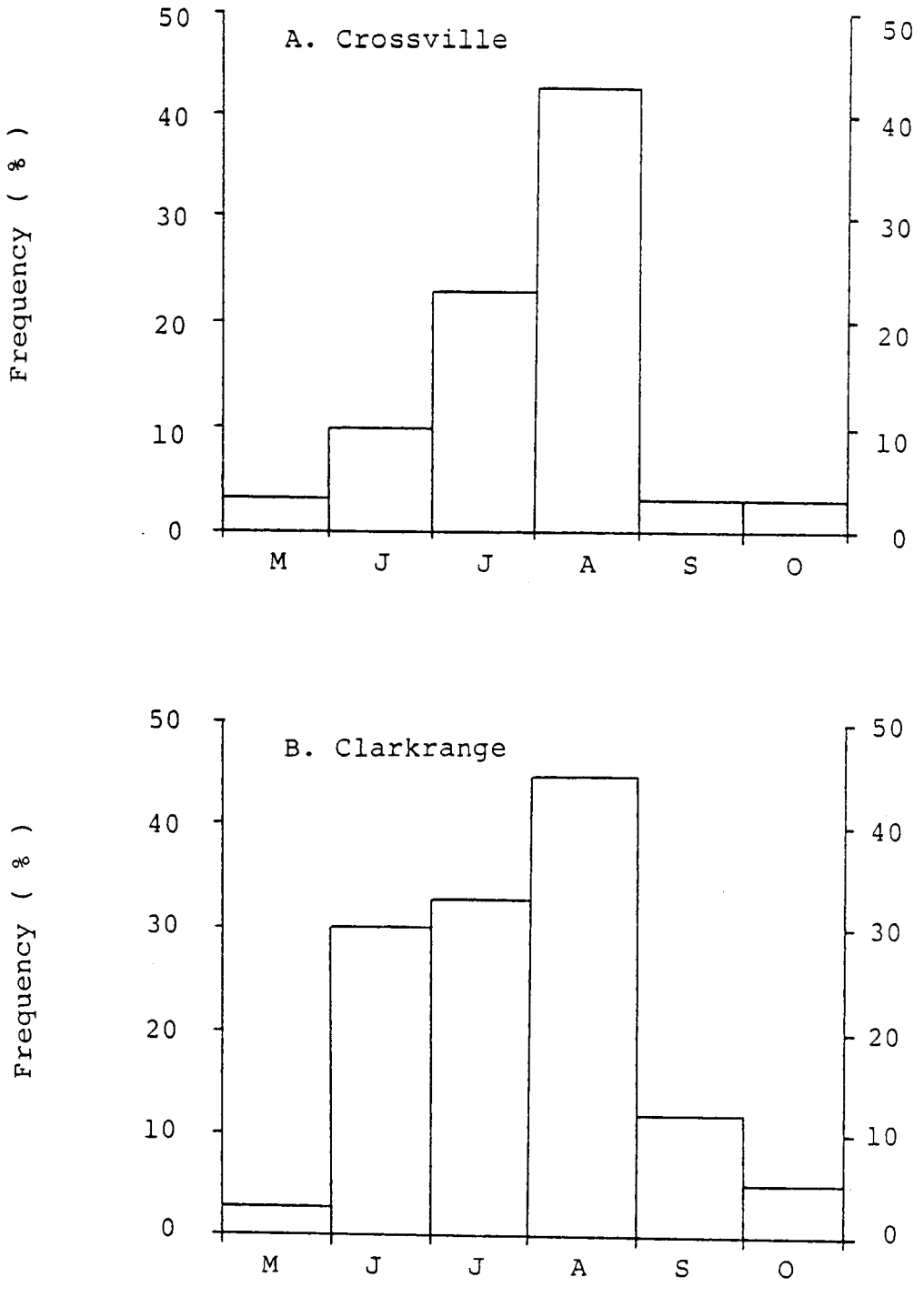

Figure 8. Monthly moisture deficits of equal or greater than 50 mm.

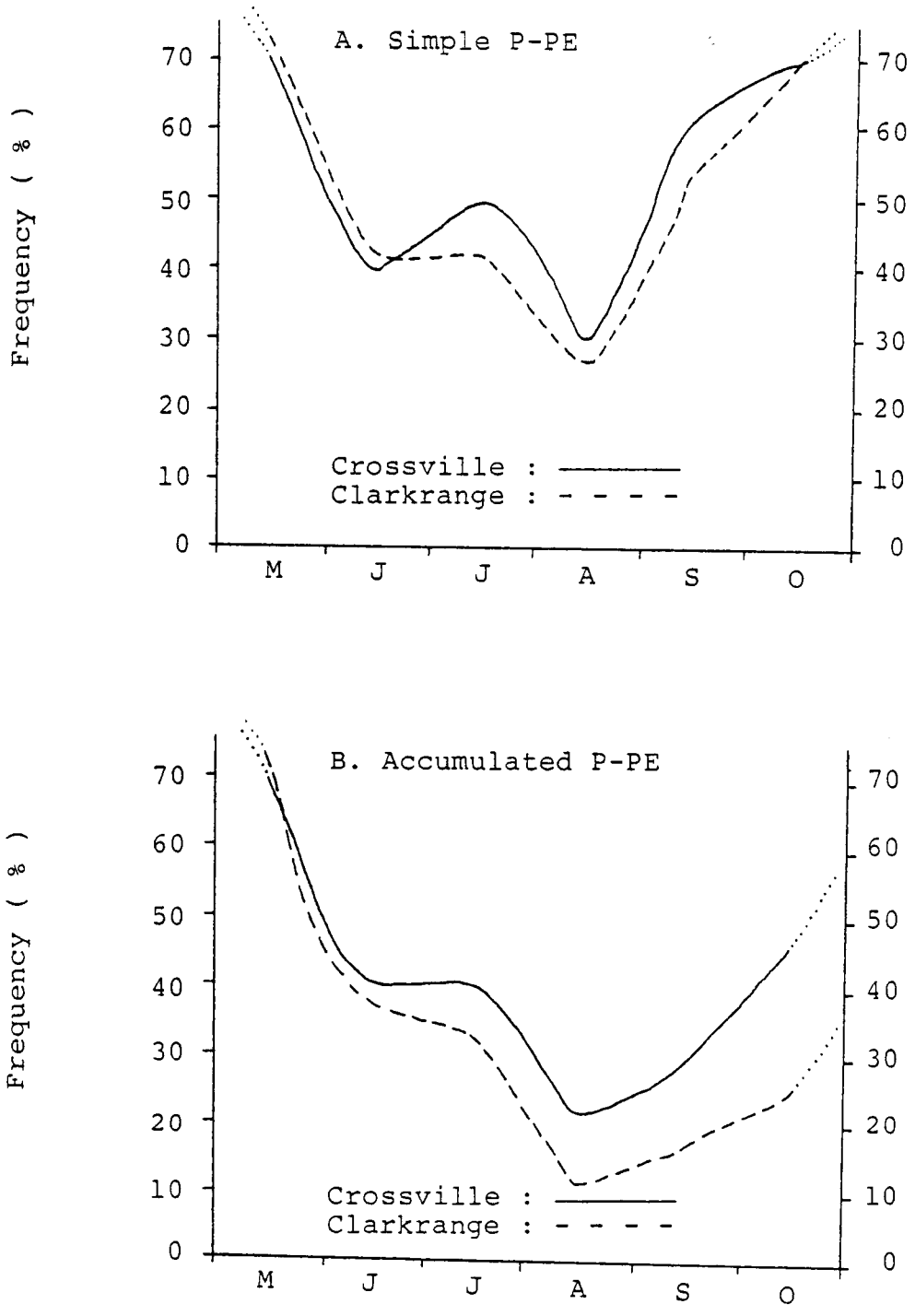

Figure 9. Probability of having no simple monthly deficit and no accumulated monthly deficit.

other months the recurrence interval was 10 years or longer and therefore considered negligible (Figure 8). In Clarkrange, the recurrence interval of 50 mm deficits was 3.0 years for July and 2.3 years for August. As in Crossville, frequencies for such deficits were close to 10% in the months of May, September, and October. Only the figures for June differ significantly. While in Crossville a deficit of equal or greater than 50 mm occurred on the average only every tenth year, it occurred in Clarkrange nearly every third year.

The similarity between the stations was also confirmed by the study of the extreme deficit values. In Crossville, deficits of more than 100 mm occurred only in four months during the 30-year study period, with an absolute extreme of 115 mm deficit in July. In Clarkrange the 100 mm threshold was exceeded only once with an extreme of 119 mm.

For the months of May, September, an October sufficient moisture supply was recorded in more than 50% of all years. In June, July, and August less than 50% of all years had sufficient moisture. August was the driest month. Only for every third year was no moisture deficit recorded (Figure 9).

Accumulated Monthly P-PE: Accumulated deficits for the months of the growing season have more practical value for the purpose of this study because they consider deficits

which were carried over from preceeding months. These are shown in Figures 10 and 11. The frequencies of accumulated deficits for 50 mm, 100 mm, and 150 mm thresholds were chosen for evaluation as were the extreme values. The 50 mm threshold was considered a moderate deficit; it depletes the moisture of the most common soil types to about 50%. The 100 mm as well as the 150 mm threshold represent severe deficits that deplete soil of different quality to at least 30% of their storage capacity.

The accumulated deficits increased from May to August and then stayed at about the same level through September and October (Figure 12 and 13) In Crossville, a deficit of 50 mm and more ocurred with a frequency of about 30 percent in July, 60 percent in August, and 40 percent in each September and October. Frequencies for May and June were so low as to be considered negligible. Deficits of 100 mm or greater had a frequency of 35 percent in August, 22 percent in September, and 28 percent in October. In May and June deficits never exceeded 100 mm. In July such severe conditions occurred on average only once in eleven years. For a deficit of equal or greater than 150 mm, considerable frequencies ocurred only in August, September, and October and were around 15 percent.

In Clarkrange, deficits of 150 mm and more ocurred with the same frequency as in Crossville. For the 50 mm and 100 mm thresholds, however, the frequencies for nearly all

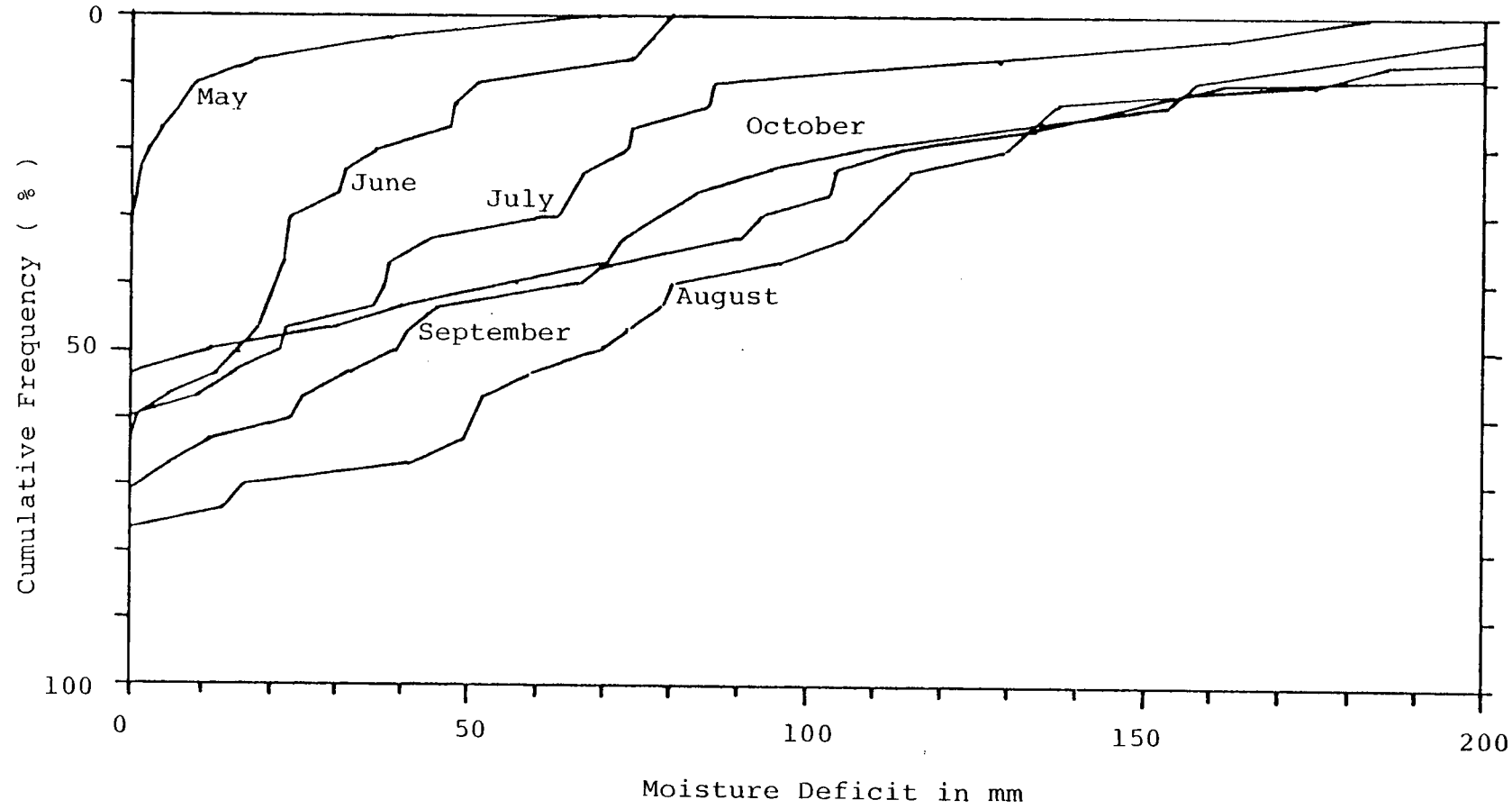

Figure 10. Accumulated moisture deficits for the months of May through October. Crossville, period of record: 1950 - 1979.

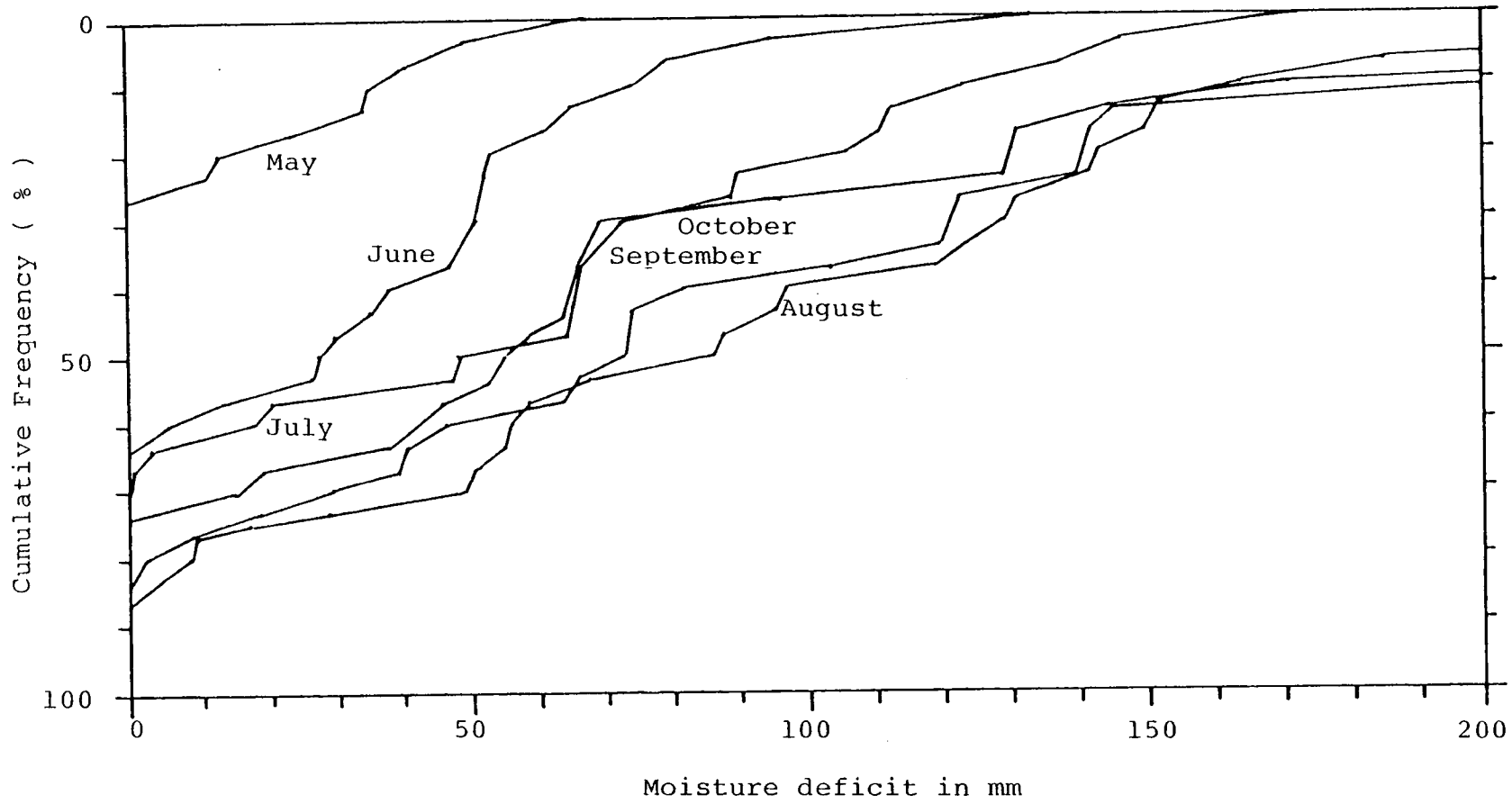

Figure 11. Accumulated moisture deficits for the months of May through October. Clarkrange, period of record: 1950 - 1979.

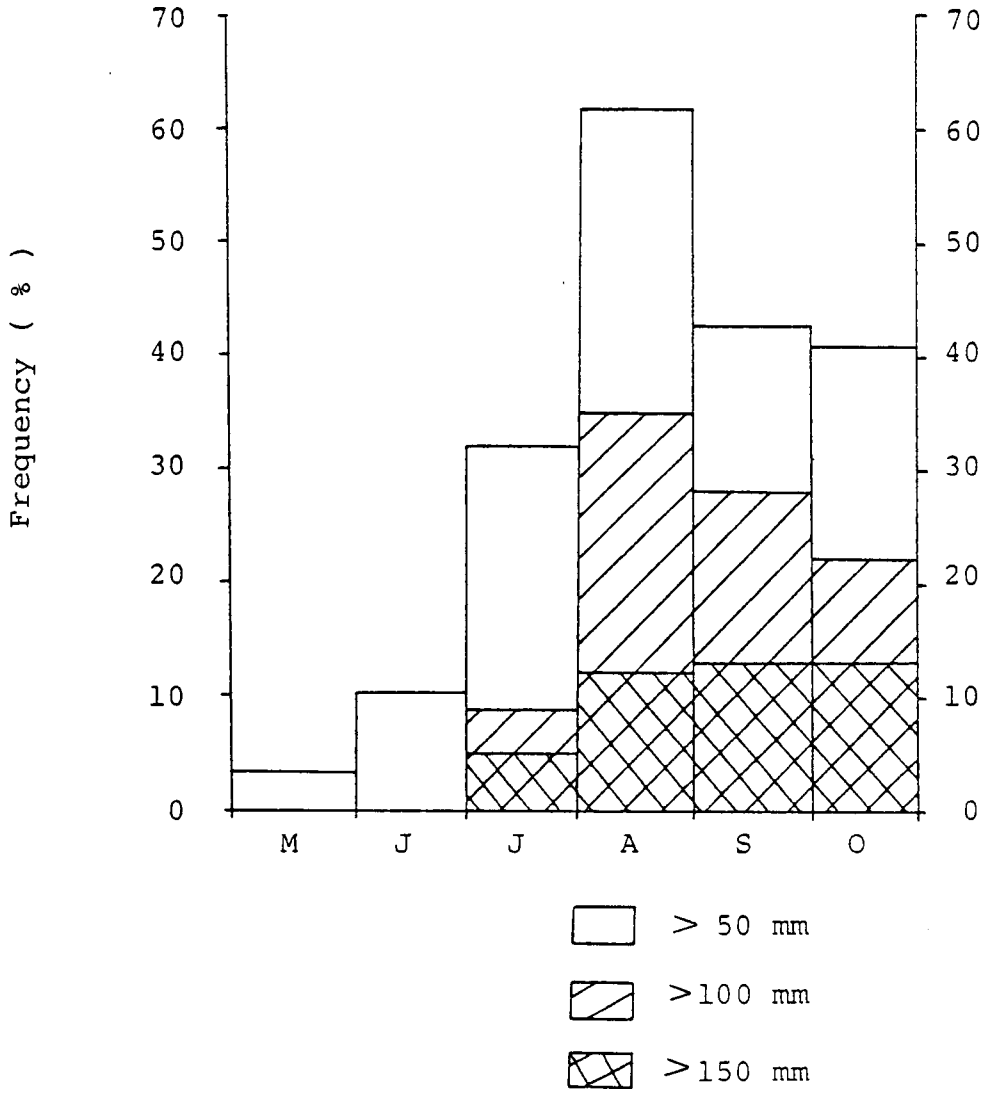

Figure 12. Probability of accumulated monthly deficits of equal or greater than 50 mm, 100 mm, and 150 mm. Data for Crossville.

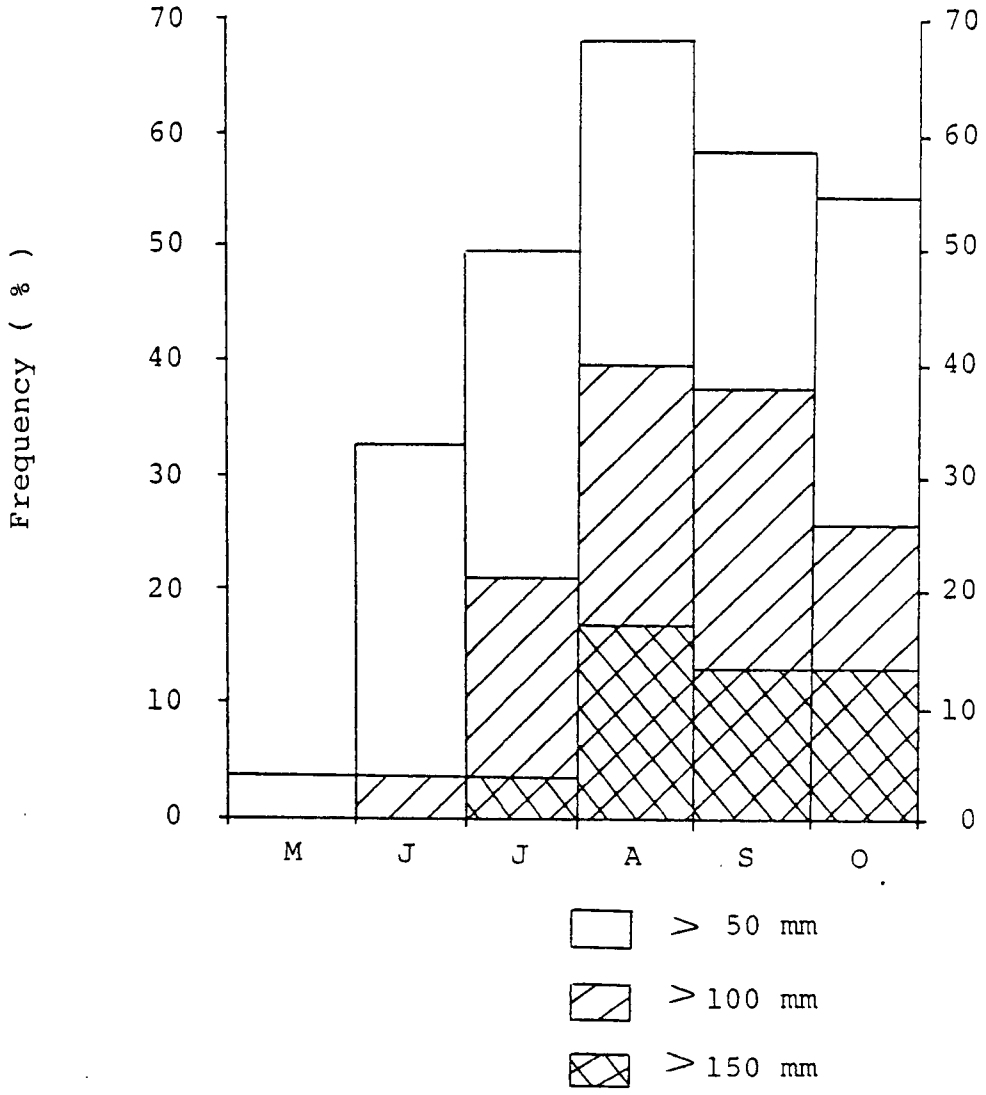

Figure 13. Probability of accumulated monthly deficits of equal or greater than 50 mm, 100 mm, and 150 mm. Data for Clarkrange.

months were about 10% higher. Deficits exceeded the 200 mm mark seven times in Crossville and nine times in Clarkrange. Those deficits ocurred in the months of August, September, and October.

For all months except May, the chance of having sufficient moisture was less than 50 percent. Moisture sufficiency was least probable in August. In this month, only about every fourth year was adequate moisture available at Crossville, and about every eigth year at Clarkrange.

The information on meteorologic moisture conditions suggests that there is a strong tendency for moisture deficits to be more severe in the late growing season rather than in the early part of the season, and the moisture regime for the southwestern part of the study area is comparable to that in the northeastern part. The frequencies of specific moisture deficits, however, are around 10 percent higher for the northeastern area. This appears to be associated with differences in precipitation, which, on the average, have values about 10 percent lower.

It should be remembered, however, that the calculation of PE values is based on temperature data at the Crossville Experiment Station alone. The elevation of this station is lower than that of most of the northeastern part of the study area. Somewhat lower PE values and somewhat smaller moisture deficits might therefore be expected for in the

northeast. Even so, meteorologic moisture conditions are probably less favorable in the northeastern part of the study area.

The temporal distribution of available moisture during the growing season is similar for both stations. Moisture deficits increase in their frequency and their severity from the early season to the late season. The increase of deficits in the late season generally results from higher deficits in the particular months in combination with already existing deficits from the previous months. Only in October are deficits the result of carried-over deficits rather than from deficits originating in the month itself.

Soil Moisture Analysis

From the meteorologic data themselves it is not possible to evaluate the impact of moisture deficits on vegetation. This can only be accomplished when the water holding capacities and the actual storage volumes of the existing soils are considered.

Table 1 which appeared in Chapter III, provides information on soil moisture holding capacities for several categories of plant with different rooting depths. For these combinations of soil texture and rooting depth the monthly water balances (Thornthwaite and Mather, 1957) were calculated. This was done for the years with the highest, the third highest, and the sixth highest deficits in the

entire growing season, as well as for the early and the late season. The results of these calculations are shown in Appendix B.

Thirty-Year Frequency and Moisture Stress: The years with the highest moisture deficit in the growing season were 1952 for Crossville and 1968 for Clarkrange. In those years soil moisture depletion proved to be extremely severe. Even soils with the largest storage capacity in the root zone (250 mm) were depleted below 50% during four consecutive months and to about one third of their capacities for two consecutive months. Soils with a storage of 100 mm or less were depleted below 50 percent for five consecutive months, below 25 percent for four consecutive months and were nearly empty (soil moisture retention less than 10 percent) for at least three months. The soil with the lowest storage capacity (60 mm) could be considered empty for the four months from July through October.

Deficits of such a magnitute and duration pose a severe stress on vegetation. The deficits appear even more significant if one consideres that the actual available moisture storage within the root zone or within the shallow soil layer frequently does not exceed values of 100 to 150 mm. Yield losses are unavoidable under these conditions. On the usually thin forest soils survival of tree seedlings and immature trees is severely reduced. Under these extreme

conditions vegetation can be stressed to the permanent wilting point.

Ten-Year Frequencies and Moisture Stress: The years with the third highest deficits in the growing season roughly represent moisture stress conditions that reccur in an interval of ten years. Such years were 1953 and 1962 for Clarkrange and for Crossville, respectively.

The stress on vegetation in these years was significant. At Clarkrange where most soils have less than 125 mm of available moisture in the root zone, moisture depletions to 25 percent or less occurred in at least three consecutive months. The shallowest soils were empty of moisture during these months. The situation in Crossville was more favorable than in Clarkrange as a result of high precipitation in June which blocked the accumulation of otherwise high deficits. Therefore, although 1962 was the year with the third highest sum of all deficits in the growing season, it is probably not representative for a soil moisture stress condition with a 10-year recurrence interval.

The data for Clarkrange seem to be more realistic in representing soil moisture conditions with a frequency of ten years. The data show that moisture stress on vegetation still is considerable, with somewhat less severe effects on deep-rooting plants on the better agricultural soils. On

shallower soils however, yield reduction and damage of tree seedlings should be expected.

Five-Year Frequencies and Moisture Stress: Finally, moisture deficit situations with a recurrence interval of five years were evaluated. The Year 1951 for Crossville and 1956 for Clarkrange had the sixth highest deficit, representing conditions that occur on the average every five years.

In both years moisture depletion is great. For soils with a storage capacity of 100 mm or less, severe depletions occur over at least three months. Soils with a larger storage capacity experience severe to moderate depletions in at least two consecutive months. Only the soil with a storage of 250 mm retained more than 50% of its moisture throughout the entire growing season.

This means that even under those moisture conditions that occur with a considerable frequency, depletion of soil moisture can be severe. Most stress occurs to shallow-rooted vegetation or vegetation on thin soils, but even moderately deep agricultural soils are effected significantly.

Permanent wilting, however, occurs only under very unfavorable soil conditions and effects only very shallow-rooted plants and plants in an immature stage of root development. Reduction of crop yield and tree growth

is very probable and seedling survival may be threatened.

Summary of Stress Frequencies and Their Severity

The meteorologic water balances indicated that moisture stress conditions are likely to be more frequent and more severe in the late part of the growing season than in the early part. The soil water balance computations confirmed this trend and revealed that the differences are significant.

In the early season severe soil moisture depletions always occured in only one of three months. Only those soils with low moisture storage capacities were severely depleted. Soils with a storage of more than 100 mm experienced severe depletions only in the driest year. Deficits within the early season frequently increased from May to July, mainly because of the accumulation of deficits.

In the late season severe soil moisture depletions are very frequent. Even under conditions with a five year recurrence interval, soils with up to 125 mm storage capacity are severely depleted for at least two consecutive months. The shallow soils with 60 mm and 75 mm in storage are likely to experience total depletion. Only soils with a storege capacity of 200 mm or more can retain over 50% of their moisture in most years.

Dry-Day Sequences

The determination of the frequencies of absolutely dry

days could be accomplished by using the data that were published by Safley (1974). The data on the frequency of dry and wet days which were given on a weekly basis were averaged to monthly mean frequencies (Table 3). The probability of dry day sequences from one to fifteen days was than calculated.

Figure 14 shows the probability of the occurrence of dry day sequences of ten days or greater and fifteen days or greater. The figures reveal that sequences of ten or more dry days are fairly uncommon in the months of May, June, July, and August. The probability of having ten consecutive dry days is about 10 percent in these months. A dry day sequence of fifteen days occurs only about once in 50 years.

The probability of such dry day sequences, however, drastically increases in the months of September and October. A 15-day dry day sequence has about a 12 percent probability and a 10-day sequence has a probability of 48 percent, which is about every other year.

The moisture deficit that results from these dry day sequences equals the daily PE times the number of dry days. Besides the absolutely dry days, however, there are also days with precipitation that can have deficits. This occurs when daily precipitation is less than the daily PE. Such days were referred to as "relatively dry days" (Table 4).

To determine the frequency and the average rainfall of relatively dry days, a test had to be made to determine

Table 3. Probability of the occurrence of "Absolutely "Absolutely Dry Days"[1].

1-Week Period beginning :		Weekly Dry[2,4]	Weekly Dry/Dry[3,4]	Monthly Averages Dry	Monthly Averages Dry/Dry
May	3	69	78		
	10	65	74		
	17	66	72	66	74
	24	68	70		
	31	64	75		
June	7	59	68		
	14	64	72		
	21	69	75	64	72
	28	65	71		
July	5	62	70		
	12	66	72		
	19	67	74	65	72
	26	65	72		
August	2	65	72		
	9	63	68		
	16	63	68	66	73
	23	70	79		
	30	69	78		
September	6	75	80		
	13	77	82		
	20	76	83	76	83
	27	77	86		
October	4	76	82		
	11	79	86		
	18	75	83	76	83
	25	75	80		

[1]Days with less than a trace of precipitation.
[2]Probability that a given day is dry.
[3]Probability that a day following a dry day will be dry.
[4]Source: Safley, J.M.,jr. 1974. Probability of sequences of wet and dry days for Tennessee. NOAA 103p.

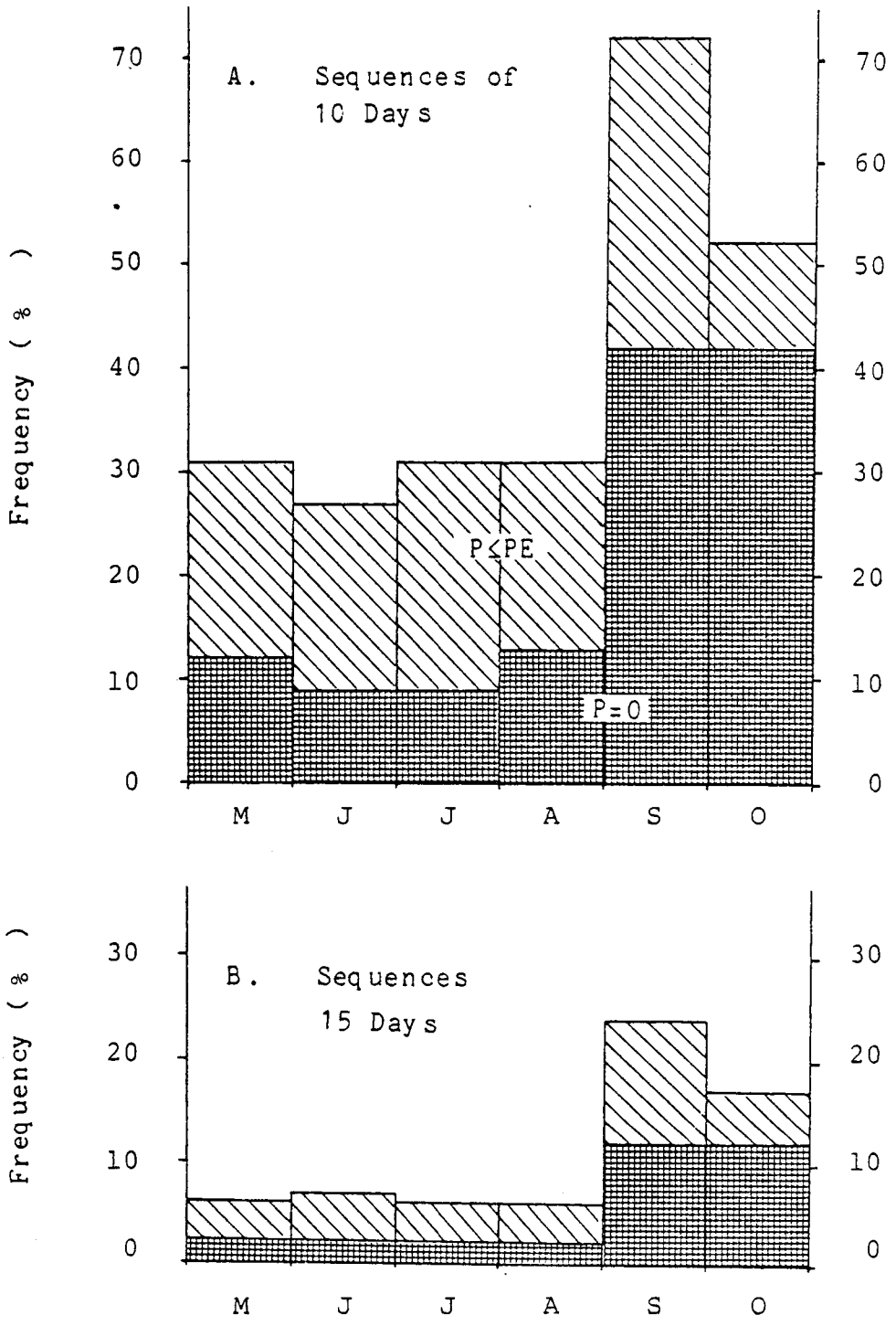

Figure 14. Frequency of dry-day sequences.

Table 4. Probability of the occurrence of "Relatively Dry Days"[1].

Month	Average Daily PE	Dry[2]	Dry/Dry[3]
May	3.0 mm	75 %	79 %
June	4.0 mm	75 %	79 %
July	4.5 mm	78 %	80 %
August	4.0 mm	78 %	80 %
September	3.0 mm	83 %	87 %
October	1.7 mm	80 %	85 %

[1]Days with a precipitation of equal or less than the daily PE.
[2]Probability that a given day is dry.
[3]Probability that a day following a dry day will be dry.

whether there is any logical relationship between the values of the frequency and the values of the corresponding precipitation threshold. This proceedure was needed to determine the probability of the occurrence of different dry days with different precipitation thresholds, because the daily precipitation thresholds vary from month to month according to the average daily PE values for those months. precipitation threshold. The existing frequency data were plotted for the thresholds of 0.254 mm (0.01 in), 1.27 mm (0.05 in), 2.54 mm (0.10 in), 5.08 mm (0.20 in), and 12.7 mm (0.50 in), that were given by Safley. Figures 15 and 16 show that the relationship of frequency and threshold are nearly linear for thresholds of 5.08 mm and less. In no month is the daily PE higher than 5.08 mm. Therefore, the graphs in Figures 15 and 16 could be used to determine the frequencies of dry days with thresholds that equaled the daily PE values of each of the six months of the growing season. The average rainfall in these relatively dry days is about half the daily PE.

Figure 13 shows the frequencies of relatively dry days. For sequences of fifteen days, only the months of September and October have significant frequencies, with probabilities of 24 percent and 17 percent, respectively. For the months from May through August the frequencies are less than 10 percent.

A sequence of ten relatively dry days, however, occurs

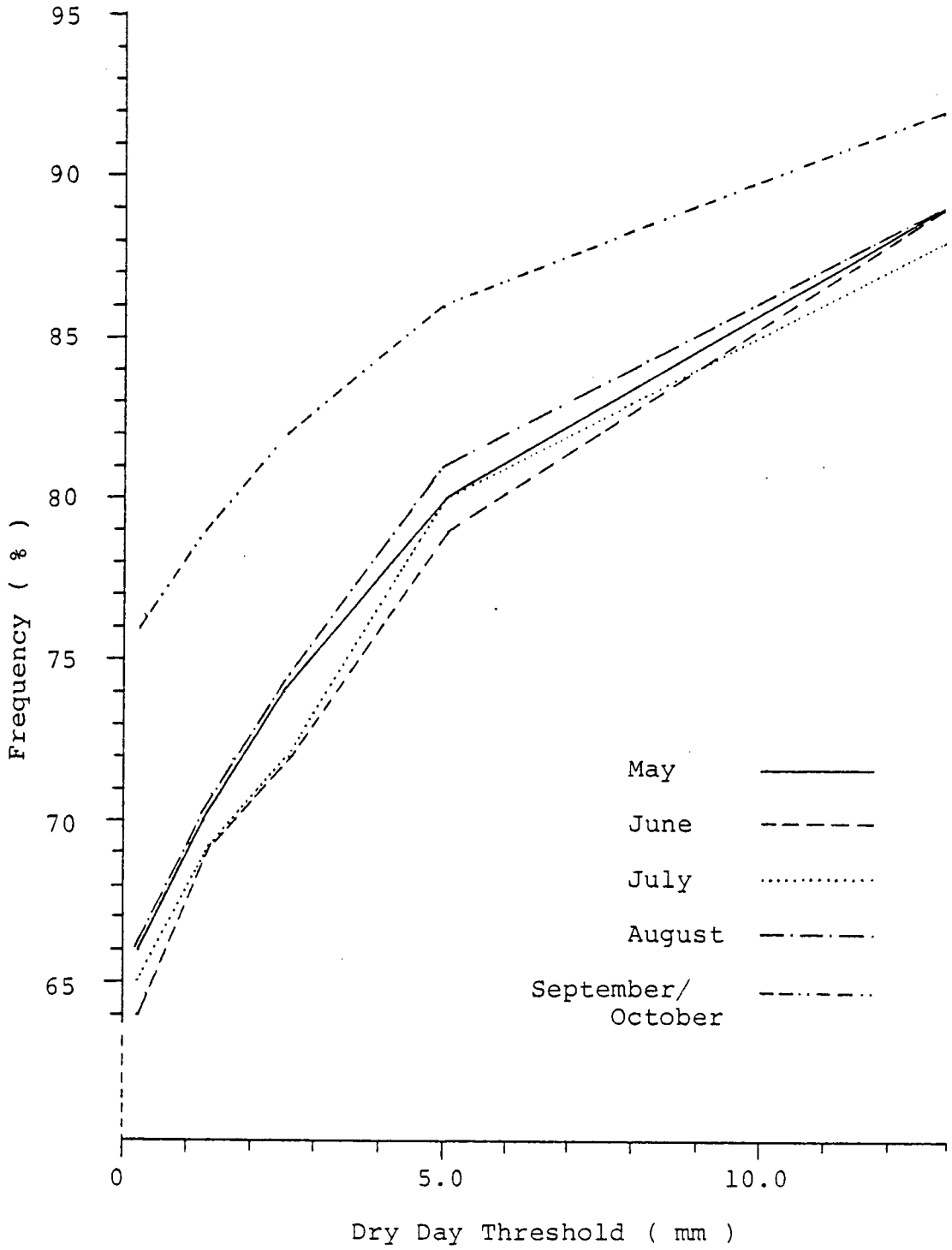

Figure 15. Probability that a given day is dry.

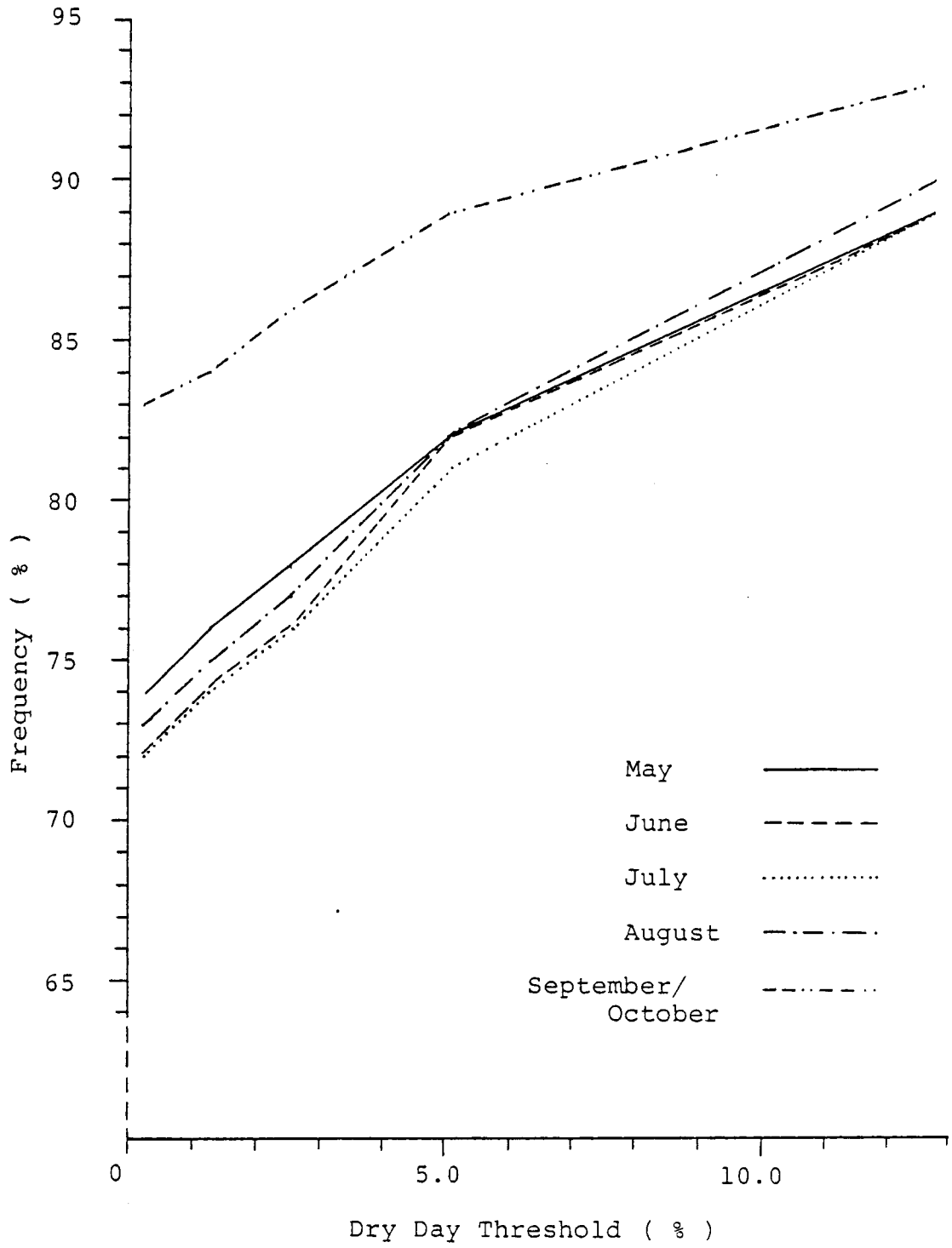

Figure 16. Probability that a day following a dry day will be dry.

with a frequency of about once in three years in May, June, July, and August, and at least once in two years in September and October. These findings confirm the results of the water balance analysis, which showed the strong tendency for the months of the late season to be drier than the months of the early season.

The next step in the study of short-term moisture stress, was to determine the soil moisture depletions that resulted from given dry day sequences. This was done with the assumption that soil moisture storage is full at the beginning of a dry day sequence. The results indicate that under this assumption only the two shallowest soils with a storage of 60 mm and 75 mm are depleted of half their moisture with a considerable frequency (more than 10%) in June and September. For soils with a larger storage capacity, the probability to be severely depleted by a single dry day sequence is extremely small.

The discussion of the long-term moisture conditions, however, made the point that full soil moisture storage at the beginning of a month, especially in the late season, is very unlikely and the usefulness of the dry-day analysis is limited. The analysis does support earlier findings that severity of soil moisture depletion increases toward the end of the growing season.

CHAPTER VI

SUMMARY AND CONCLUSION

Summary

Moisture stress on vegetation has been shown to be relatively frequent in the study area. Plants most effected are those with a limited root system or where they are on shallow soils. There is a definite trend that soil moisture depletions increase from southwest to northeast. as a result of prevailing meteorologic conditions. The northeastern section of the study area additionally is characterized by the dominance of shallow soils on moderately steep to steep slopes. The combination of both. the meteorologic and soil conditions. lead to distinct spatial differences in the potential for moisture stress on vegetation. In the northeastern part of the study area the potential for moisture stress is much higher than in the southwestern part.

Temporal differences of moisture stress are marked as well. Moisture deficits increase steadily from May to October. Moisture conditions in the late growing season are significantly less favorable than in the early season. The actual moisture conditions may be somewhat more severe than is shown by the soil water budgets because the water budget calculations assumed no runoff as long as PE exceeds the precipitation. A short but intense rainy period might

create a considerable amount of runoff which would not be considered going to storage in this analysis.

Conclusion

Although there are marked differences in the physical environment of forest land and agricultural land in the study area. agriculture as well as forestry face problems due to frequent and severe moisture stress on vegetation.

Most land used for agriculture in the study area has deeper soils than forest lands of the area and therefore experience less severe moisture depletions. Nevertheless. the impact of moisture deficits can be significant because crops do not always utilize the potentially available soil depth and the water stored in it during a period of a few weeks in which their root system is not fully developed. These periods of incomplete root development occur in the early part of the growing season when moisture conditions are less critical than in the late part of the season. Even so. dry spells of considerable length can occur in the early months of the growing season .as the study on dry day sequences indicated. Stresses adequate to threaten seedling survival are quite likely . The later a crop is planted the higher the risk that it becomes subject to a moisture shortage during its seedlings stage.

It is particularily interesting that the production of soybeans in the study area has steadily increased through

the last years. Soybeans are planted relatively late in the season. The period of planting generally extents from late May to the middle of June. which is about one month later than the average planting time for corn. Additionally . soybeans grow very late into the season. harvesting occurring in late October to mid-November. The critical moisture sensitive period of soybeans. if planted in late May falls in August. which is a month with high drought risk. Nevertheless. the planting of soybeans is being extended. while the findings of this study would suggest that the crop is not well adapted to the timing of moisture stresses here. The evaluation of the actual economic cost from such stresses is beyond the scope of this study.

Besides the increased planting of soybeans. the emphasis on vegetable production is also somewhat surprising. Vegetables usually have a relatively shallow root system. As has been shown shallow rooting vegetation is most frequently and most severely effected by moisture stress. Consistant with the findings of this study most vegetable production in the study area involves irrigation. Water for irrigation. however. is also in short supply over most of the area so that this practice cannot become widespread.

As discussed in Chapter II. groundwater is generally not available in the quantities needed for large scale irrigation. Surface water volumes have strong annual

fluctuations and are especially low during the growing season. Moreover. most of the agriculturally used areas are on the higher-lying plateau surface whereas major drainageways are mostly at considerably lower elevations.

From a perspective of moisture supply. deep rooting crops with critical moisture sensitive stages in the early season are more suited for the study area than crops that have a shallow root system and that have moisture senstive periods in the late part of the growing season.

For most of the forests in the study area. the probability of severe moisture stress is greater than for agricultural areas. Although trees have a grater rooting depth than most crops. the actual storage volume they can draw from is generally very limited because forests occupy the moderately steep to steep sloping areas that are characterized by thin and stony soils.

The effect of slope and aspect on moisture conditionso of the soil needs to be mentioned . On southfacing slopes PE values can be expected to be higher than on northfacing slopes. This means that water stress is more likely to occur on southfacing slopes rather than northfacing slopes. other criteria being equal. The impact of aspect and slope is difficult to quantify and should subject to further study.

Generally. the study has shown that because of thin soils and low total volume of soil moisture it is reasonable

to expect trees to suffer severe moisture stresses quite frequently. Survival of tree seedlings is threatened, especially on newly replanted plots where there is no protective tree canopy to reduce transpiration rates of seedlings. Furthermore. the study suggests that tree species best suited for the area are those whose shoot and radial growth is related mainly to the moisture supply in the early season rather than trees whose growth is related strongly to moisture conditions in the late season of the previous year.

Loblolly pine and Shortleaf pine appear best suited here because they do not have the critical late summer stress period. Their growth depends largely on the moisture supply of the current year. The Shortleaf pine is in fact the most planted softwood species. The findings of this study suggest that. from the point of view of moisture supply. large scale production of these pine species is feasible if seedling failure can be limited.

Critique

Two methods have been used in this study to evaluate the potential of moisture stress in the study area.

Thornthwaite's water balance method was used to deal with long-term moisture conditions. The results of the water balance calculations gave valuable information on frequencies and magnitutes of moisture deficits. as well as

on the temporal variations of moisture conditions throughout the growing season. Although the water balance method contains some weaknesses. the results of this method were considered sufficiently accurate enough for the purpose of this study.

The second method, a determination of the frequencies of dry day sequences and corresponding soil moisture depletions. proved to be of limited usefulness. The assumption of full soil moisture storage at the beginning of any given dry day sequence was unrealistic and understates the frequencies of specific soil moisture shortages. To achieve better dry-day values daily water budget computations for the entire study period would have been more appropriate . however. the calculations of the frequencies of dry day sequences can give a general idea on the reliability of rainfall in the months of the growing season and on the potential of moisture stress.

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APPENDICES

APPENDIX A

APPENDIX A

Abbreviations and Definitions

P	precipitation
PE	potential evapotranspiration
P-PE	meteorologic moisture surpluses or deficits
simple P-PE	P-PE that occurred in a given month
accumulated P-PE	P-PE that has been accumulated through the preceeding months
WHC	water holding capacity
soil moisture stress:	
moderate	less than 50% of the original moisture is retained
severe	less than 33% of the original moisture is retained
total depletion	less than 10% of the original moisture is retained
absolutely dry day	day that receives not more than a trace of precipitation
relatively dry day	day with a precipitation of less than the average daily PE of the corresponding month

APPENDIX B

Table B - 1. Water balance; Crossville, 1951.

	M	J	J	A	S	O
P	76	106	70	33	124	52
PE	83	121	134	132	93	55
P-PE	-7	-15	-64	-99	31	-3
Cum(P-PE)	-7	-22	-86	-185	-154	-157
60 mm WHC	53	39	8	1	2	2
75 mm WHC	68	55	23	6	9	9
100 mm WHC	93	80	41	15	21	20
125 mm WHC	118	104	62	28	36	35
150 mm WHC	143	129	84	43	52	52
200 mm WHC	193	179	129	78	92	90
250 mm WHC	243	229	176	118	134	132

Table B - 2. Water balance; Crossville, 1952.

	M	J	J	A	S	O
P	82	71	40	46	56	19
PE	91	139	145	132	83	35
P-PE	-9	-68	-105	-86	-27	-39
Cum(P-PE)	-9	-77	-182	-268	-295	-311
60 mm WHC	51	15	1	0	0	0
75 mm WHC	66	26	6	2	1	1
100 mm WHC	91	45	15	6	5	4
125 mm WHC	116	67	29	14	11	10
150 mm WHC	141	89	44	24	20	18
200 mm WHC	191	135	80	51	45	41
250 mm WHC	241	183	120	85	76	71

Table B - 3. Water balance; Crossville, 1953.

	M	J	J	A	S	O
P	115	104	160	46	54	19
PE	102	135	138	115	90	58
P-PE	13	-31	22	-69	-36	-39
Cum(P-PE)	-	-31	-9	-78	-114	-153
60 mm WHC	60	32	51	12	6	3
75 mm WHC	75	49	66	25	15	9
100 mm WHC	100	73	91	45	31	21
125 mm WHC	125	97	116	66	49	36
150 mm WHC	150	122	141	88	69	53
200 mm WHC	200	171	191	135	112	92
250 mm WHC	250	221	241	182	158	135

Table B - 4. Water balance; Crossville, 1954.

	M	J	J	A	S	O
P	118	77	45	43	87	113
PE	65	124	160	143	108	49
P-PE	52	-47	-115	-100	-21	64
Cum(P-PE)	52	-47	-162	-262	-283	-219
60 mm WHC	60	23	2	0	0	0
75 mm WHC	75	39	8	2	2	4
100 mm WHC	100	62	19	7	6	11
125 mm WHC	125	84	33	15	13	21
150 mm WHC	150	109	50	25	22	34
200 mm WHC	200	158	88	53	48	66
250 mm WHC	250	207	130	87	80	103

Table B - 5. Water balance; Crossville. 1962.

	M	J	J	A	S	O
P	47	192	60	56	193	149
PE	116	117	134	129	87	58
P-PE	-69	75	-74	-73	106	91
Cum(P-PE)	-69	6	-74	-147	-41	50
60 mm WHC	14	60	13	3	26	60
75 mm WHC	29	75	27	10	43	75
100 mm WHC	49	100	47	22	66	100
125 mm WHC	71	125	68	38	89	125
150 mm WHC	93	150	90	55	113	150
200 mm WHC	141	200	138	95	162	200
250 mm WHC	188	250	185	138	212	250

Table B - 6. Water balance; Crossville. 1968.

	M	J	J	A	S	O
P	113	38	85	84	47	85
PE	83	121	138	136	83	49
P-PE	30	-74	-53	-48	-36	36
Cum(P-PE)	30	-74	-127	-175	-211	-175
60 mm WHC	60	13	4	2	1	2
75 mm WHC	75	27	13	7	4	7
100 mm WHC	100	47	27	17	11	17
125 mm WHC	125	68	44	30	20	30
150 mm WHC	150	90	63	46	36	46
200 mm WHC	200	138	105	82	69	82
250 mm WHC	250	185	150	123	107	123

Table B - 7. Water balance; Crossville. 1977.

	M	J	J	A	S	O
P	127	91	90	82	186	160
PE	98	121	145	129	93	38
P-PE	29	-30	-55	-47	93	122
Cum(P-PE)	29	-30	-85	-132	-39	83
60 mm WHC	60	33	10	4	27	60
75 mm WHC	75	50	23	12	44	75
100 mm WHC	100	74	42	26	67	100
125 mm WHC	125	98	62	42	90	125
150 mm WHC	150	122	84	61	114	150
200 mm WHC	200	172	130	102	164	200
250 mm WHC	250	222	177	146	213	250

Table B - 8. Water balance; Clarkrange, 1952.

	M	J	J	A	S	O
P	96	85	26	81	70	20
PE	91	139	145	132	83	35
P-PE	5	-54	-119	-51	-13	-15
Cum(P-PE)	5	-54	-173	-224	-237	-252
60 mm WHC	60	19	2	1	0	0
75 mm WHC	75	35	7	3	3	2
100 mm WHC	100	58	17	10	9	8
125 mm WHC	125	80	30	20	18	16
150 mm WHC	150	104	46	33	30	27
200 mm WHC	200	152	83	64	60	56
250 mm WHC	250	201	124	101	96	90

Table B - 9. Water balance; Clarkrange, 1953.

	M	J	J	A	S	O
P	184	83	125	38	48	11
PE	102	135	138	115	90	58
P-PE	82	-52	-13	-77	-42	-47
Cum(P-PE)	82	-52	-65	-142	-184	-231
60 mm WHC	60	20	16	3	1	1
75 mm WHC	75	36	31	11	6	3
100 mm WHC	100	59	51	23	15	9
125 mm WHC	125	82	73	39	28	19
150 mm WHC	150	106	97	57	43	31
200 mm WHC	200	153	144	97	79	62
250 mm WHC	250	203	192	141	119	99

Table B - 10. Water balance; Clarkrange, 1955.

	M	J	J	A	S	O
P	102	139	101	38	86	67
PE	102	99	149	136	105	47
P-PE	0	40	-48	-98	-19	20
Cum(P-PE)	0	40	-48	-146	-165	-145
60 mm WHC	60	60	22	3	2	3
75 mm WHC	75	75	38	10	8	10
100 mm WHC	100	100	61	22	18	23
125 mm WHC	125	125	84	38	32	38
150 mm WHC	150	150	108	55	49	56
200 mm WHC	200	200	157	96	87	96
250 mm WHC	250	250	206	139	128	139

Table B - 11. Water balance; Clarkrange, 1956.

	M	J	J	A	S	O
P	48	37	204	91	44	63
PE	98	121	141	125	83	58
P-PE	-50	-84	63	-34	-39	5
Cum(P-PE)	-50	-134	-71	-105	-144	-139
60 mm WHC	21	4	14	7	3	3
75 mm WHC	38	12	28	18	10	11
100 mm WHC	60	25	48	34	23	24
125 mm WHC	83	41	70	53	39	40
150 mm WHC	107	60	92	74	56	58
200 mm WHC	155	102	140	118	96	99
250 mm WHC	204	145	188	164	140	143

Table B - 12. Water balance; Clarkrange, 1962.

	M	J	J	A	S	O
P	75	96	58	58	153	146
PE	116	117	134	129	87	58
P-PE	-41	-21	-76	-71	65	88
Cum(P-PE)	-41	-62	-138	-209	-143	-55
60 mm WHC	26	17	3	1	3	19
75 mm WHC	43	32	11	4	10	35
100 mm WHC	66	53	24	12	23	57
125 mm WHC	89	75	40	23	39	80
150 mm WHC	113	98	59	36	57	103
200 mm WHC	162	146	99	69	97	151
250 mm WHC	212	194	143	107	140	200

Table B - 13. Water balance; Clarkrange, 1963.

	M	J	J	A	S	O
P	88	121	158	66	39	0
PE	87	117	126	122	87	67
P-PE	1	4	32	-56	-48	-67
Cum(P-PE)	1	4	32	-56	-104	-171
60 mm WHC	60	60	60	19	7	2
75 mm WHC	75	75	75	35	18	7
100 mm WHC	100	100	100	56	34	17
125 mm WHC	125	125	125	79	53	31
150 mm WHC	150	150	150	103	74	47
200 mm WHC	200	200	200	151	118	84
250 mm WHC	250	250	250	199	165	125

Table B - 14. Water balance; Clarkrange, 1968.

	M	J	J	A	S	O
P	99	41	69	58	50	69
PE	83	121	138	136	83	49
P-PE	16	-80	-67	-78	-33	2
Cum(P-PE)	16	-80	-147	-225	-258	-238
60 mm WHC	60	11	3	1	0	0
75 mm WHC	75	25	10	3	2	3
100 mm WHC	100	44	22	10	7	9
125 mm WHC	125	65	38	20	15	18
150 mm WHC	150	87	55	33	26	30
200 mm WHC	200	133	95	64	54	60
250 mm WHC	250	181	138	101	88	96

Table B - 15. Water balance; Clarkrange, 1974.

	M	J	J	A	S	O
P	138	49	74	112	122	51
PE	94	102	134	118	77	44
P-PE	44	-53	-60	-6	45	7
Cum(P-PE)	44	-53	-113	-119	-74	-67
60 mm WHC	60	20	6	5	13	15
75 mm WHC	75	36	18	17	27	30
100 mm WHC	100	58	31	30	47	50
125 mm WHC	125	81	54	51	68	72
150 mm WHC	150	105	70	67	90	95
200 mm WHC	200	153	113	109	138	142
250 mm WHC	250	202	159	155	185	190

Table B - 16. Water balance; Clarkrange, 1976.

	M	J	J	A	S	O
P	145	111	66	42	70	144
PE	76	117	126	118	80	38
P-PE	69	-6	-60	-76	-10	106
Cum(P-PE)	69	-6	-66	-142	-152	-46
60 mm WHC	60	54	15	3	3	23
75 mm WHC	75	69	30	11	9	39
100 mm WHC	100	94	51	23	21	62
125 mm WHC	125	119	73	39	36	85
150 mm WHC	150	144	96	57	53	110
200 mm WHC	200	194	143	97	93	158
250 mm WHC	250	244	191	141	135	208

WATER BALANCES

The preceeding tables show the soil moisture retentions that were obtained by applying the water balance method. Soil moisture retention values are given for seven soils with different total WHC in the root zone.

All values in the tables are in mm.

Key :

	Crossville			Clarkrange		
	GS[1]	I[2]	II[3]	GS	I	II
1st[4]	1952	1952	1953	1968	1952	1963
3rd[5]	1962	1968	1952	1953	1962	1955
6th[6]	1951	1977	1954	1956	1974	1976

1 entire growing season (May through October)
2 first half of the growing season
3 second half of the growing season
4 highest deficit (P-PE) for the 30-year study period
5 third highest deficit
6 sixth highest deficit

APPENDIX C

Table C - 1. Frequencies of sequences of "Absolutely Dry Days" in May.

Length of Dry-Day Sequence in n Days n	Probability of Occurrence %	Total Number of Days that belong to a Dry-Day Sequence of n or more Days	Total Number of Sequences of n Days or more
1	66	20.5	20.46
2	49	15.2	7.60
3	36	11.2	3.72
4	27	8.4	2.09
5	20	6.2	1.24
6	15	4.7	0.78
7	11	3.4	0.49
8	8	2.5	0.31
9	6	1.9	0.21
10	4	1.2	0.12
11	3	0.9	0.08
12	2	0.6	0.05
13	2	0.6	0.05
14	1	0.3	0.02
15	1	0.3	0.02

Table C - 2. Frequencies of sequences of "Absolutely Dry Days" in June.

Length of Dry-Day Sequence in n Days n	Probability of Occurrence %	Total Number of Days that belong to a Dry-Day Sequence of n or more Days	Total Number of Sequences of n Days or more
1	64	19.2	19.20
2	46	13.8	6.90
3	33	9.9	3.30
4	24	7.2	1.80
5	17	5.1	1.02
6	12	3.6	0.60
7	9	2.7	0.39
8	6	1.8	0.23
9	5	1.5	0.17
10	3	0.9	0.09
11	2	0.6	0.05
12	2	0.6	0.05
13	1	0.3	0.02
14	1	0.3	0.02
15	1	0.3	0.02

Table C - 3. Frequencies of sequences of "Absolutely Dry Days" in July.

Length of Dry-Day Sequence in n Days n	Probability of Occurrence %	Total Number of Days that belong to a Dry-Day Sequence of n or more Days	Total Number of Sequences of n Days or more
1	65	20.2	20.15
2	47	14.6	7.29
3	34	10.4	3.51
4	24	7.4	1.49
5	17	5.3	1.05
6	13	4.0	0.67
7	9	2.8	0.40
8	7	2.2	0.27
9	5	1.6	0.17
10	3	0.9	0.09
11	2	0.6	0.06
12	2	0.6	0.05
13	1	0.3	0.02
14	1	0.3	0.02
15	1	0.3	0.02

Table C - 4. Frequencies of sequences of "Absolutely Dry Days" in August.

Length of Dry-Day Sequence in n Days n	Probability of Occurrence %	Total Number of Days that belong to a Dry-Day Sequence of n or more Days	Total Number of Sequences of n Days or more
1	66	20.5	20.46
2	48	14.9	7.44
3	35	10.9	3.62
4	26	8.1	2.02
5	19	5.9	1.18
6	14	4.3	0.72
7	10	3.1	0.44
8	7	2.2	0.27
9	5	1.6	0.17
10	4	1.3	0.13
11	3	0.9	0.08
12	2	0.6	0.05
13	2	0.6	0.05
14	1	0.3	0.02
15	1	0.3	0.02

Table C - 5. Frequencies of sequences of "Absolutely Dry Days" in September and October.

Length of Dry-Day Sequence in n Days n	Probability of Occurrence %	Total Number of Days that belong to a Dry-Day Sequence of n or more Days	Total Number of Sequences of n Days or more
1	76	22.8	22.80
2	63	18.9	9.45
3	52	15.6	5.20
4	43	12.9	3.23
5	36	10.8	2.16
6	30	9.0	1.50
7	25	7.5	1.07
8	21	6.3	0.79
9	17	5.1	0.57
10	14	4.2	0.42
11	12	3.6	0.33
12	10	3.0	0.25
13	8	2.4	0.18
14	7	2.1	0.15
15	6	1.8	0.12

Table C - 6. Frequencies of sequences of "Relatively Dry Days" in May and June.

Length of Dry-Day Sequence in n Days n	Probability of Occurrence %	Total Number of Days that belong to a Dry-Day Sequence of n or more Days	Total Number of Sequences of n Days or more
1	75	22.5	22.50
2	59	17.7	8.85
3	47	14.1	4.70
4	37	11.1	2.78
5	29	8.7	1.74
6	23	6.9	1.15
7	18	5.4	0.77
8	14	4.2	0.53
9	11	3.3	0.37
10	9	2.7	0.27
11	7	2.1	0.19
12	6	1.8	0.15
13	4	1.2	0.09
14	4	1.2	0.09
15	3	0.9	0.07

Table C - 7. Frequencies of sequences of "Relatively Dry Days" in July and August.

Length of Dry-Day Sequence in n Days n	Probability of Occurrence %	Total Number of Days that belong to a Dry-Day Sequence of n or more Days	Total Number of Sequences of n Days or more
1	78	24.2	24.18
2	62	19.2	9.61
3	50	15.5	5.17
4	40	12.4	3.10
5	32	9.9	1.98
6	26	8.1	1.34
7	20	6.2	0.89
8	16	5.0	0.62
9	13	4.0	0.45
10	10	3.1	0.31
11	8	2.5	0.23
12	7	2.2	0.18
13	5	1.6	0.12
14	4	1.2	0.09
15	3	0.9	0.06

Table C - 8. Frequencies of sequences of "Relatively Dry Days" in September.

Length of Dry-Day Sequence in n Days n	Probability of Occurrence %	Total Number of Days that belong to a Dry-Day Sequence of n or more Days	Total Number of Sequences of n Days or more
1	83	24.9	24.90
2	72	21.6	10.80
3	63	18.9	6.30
4	55	16.5	4.13
5	48	14.4	2.88
6	41	12.3	2.05
7	36	10.8	1.54
8	31	9.3	1.16
9	27	8.1	0.90
10	24	7.2	0.72
11	21	6.3	0.57
12	18	5.4	0.47
13	16	4.8	0.37
14	14	4.2	0.30
15	12	2.6	0.24

Table C - 9. Frequencies of sequences of "Relatively Dry Days" in October.

Length of Dry-Day Sequence in n Days n	Probability of Occurrence %	Total Number of Days that belong to a Dry-Day Sequence of n or more Days	Total Number of Sequences of n Days or more
1	80	24.8	24.80
2	68	21.1	10.54
3	58	18.0	5.99
4	49	15.2	3.80
5	42	13.0	2.60
6	35	10.9	1.81
7	30	9.3	1.33
8	26	8.1	1.01
9	22	6.8	0.76
10	19	5.9	0.59
11	16	5.0	0.45
12	13	4.0	0.34
13	11	3.4	0.26
14	10	3.1	0.22
15	8	2.5	0.17

VITA

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Mr. Schumann entered the University of Tennessee, Knoxville in September, 1981, as a non-degree special student. He was admitted to the Graduate School in March, 1982. In September, 1982, he was accepted as a Graduate Teaching Assistant in the Geography Department of the University of Tennessee. He received the Master of Science degree with a major in geography in March, 1984.
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