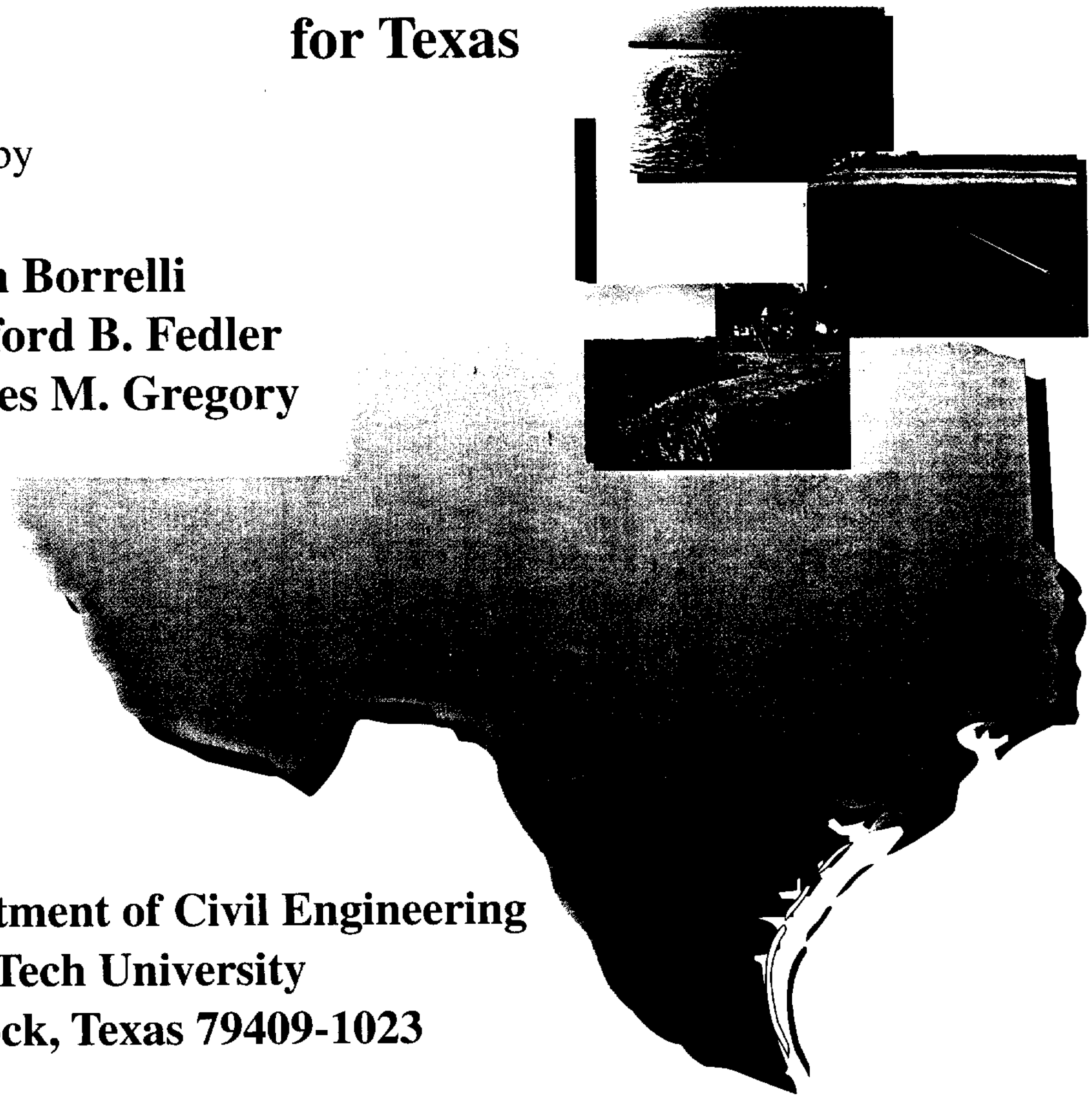
Mean Crop Consumptive Use and Free-Water Evaporation for Texas

by

John Borrelli
Clifford B. Fedler
James M. Gregory



Department of Civil Engineering
Texas Tech University
Lubbock, Texas 79409-1023

Texas Water Development Board
Grant No. 95-483-137
February 1, 1998

Mean Crop Consumptive Use and Free-Water Evaporation for Texas

by

John Borrelli
Clifford B. Fedler
James M. Gregory

RECEIVED
FEB 20 1998
REGIONAL PLANNING & PROJECTS

Department of Civil Engineering
Texas Tech University
Lubbock, TX 79409-1023
Telephone: 806-742-3481 ext. 229
FAX: 806-742-3488

Texas Water Development Board
Grant No. 95-483-137
February 1, 1998

Acknowledgments

This manual was developed by the Department of Civil Engineering, Texas Tech University, under Grant No. 95-483-137 with the Texas Water Development Board. The contract manager was Mr. Comer Tuck, Texas Water Development Board.

Special acknowledgements are due to Dr. Larry O. Pochop, Department of Civil Engineering, University of Wyoming, to Dr. Robert W. Hill, Biological and Irrigation Engineering Department, Utah State University, and to Dr. Daniel R. Krieg, Department of Plant and Soil Science, Texas Tech University, for their review of this manual and the procedures used to estimate grass reference evapotranspiration. Their reviews provided valuable technical evaluations of the procedures and technical information used to develop this manual.

Acknowledgements are also due to the following graduate students who were integral partners in making the many calculations and drawing required for the preparation of this manual: Ms. Julie Ann Tietz, Jatinder Patro, Aziz Ahmed, Laxman Obalapuram, and Veeresh Sarangmath. Their conscientious performance of the many tedious calculations is greatly appreciated.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

Water is a key resource in the economic life of any area. To insure proper management of water as a resource, it is necessary first, to quantify the amount of water available and second, to quantify the amount of water required for the various uses. This manual provides information on the amounts of water consumptively used by vegetation and of evaporation from free-water surfaces. The estimated long-term consumptive use and evaporation of water presented in this manual are intended to provide a database on which decisions regarding allocation of water resources can be made.

Potential uses of the data include the following:

Potential Uses for ET Data

- The beneficial use of water needed to establish water rights.
- Estimates of turfgrass water requirements and associated default irrigation schedules for turf irrigation systems.
- Water requirements for sizing land application systems for municipal wastewater reuse systems.
- Sizing water storage reservoirs.
- Providing consumptive use inputs for long-term water balances.
- Sizing various types of conveyance structures for irrigation and municipal water supplies.

Definition of Key Terms

To use this manual correctly, it is necessary to understand the meaning of key terms. Definitions of the key terms from the field of evapotranspiration are:

Crop Consumptive Use: The total amount of water taken up by vegetation for transpiration or building of plant tissue, plus the unavoidable evaporation of soil moisture, snow, and intercepted precipitation associated with vegetal growth; synonymous with evapotranspiration

(evapotranspiration doesn't include the small amount of water used for building plant tissue) (Jensen et al., 1990).

Crop Irrigation Requirement: The quantity of water, exclusive of effective growing season precipitation, winter precipitation stored in the root zone, or (perhaps) upward water movement from a shallow water table, that is required as an irrigation application to meet the evapotranspiration needs of the crop. It also may include water requirements for germination, frost protection, prevention of wind erosion, leaching of salts, and plant cooling (Hill, 1994).

Evaporation: The physical process by which a liquid or solid is transformed to the gaseous state, which usually is restricted to the change of water from liquid to gas (Jensen et al., 1990).

Definition ET

Evapotranspiration: The combined processes by which water is transferred from the earth's surface to the atmosphere; evaporation of liquid or solid water plus transpiration from plants (Jensen et al., 1990).

For the definition of other terms related to consumptive use of water and free-water evaporation, please see the Glossary of Terms.

Contents of Manual

Included in this manual are long-term estimates of grass reference crop evapotranspiration using the Penman-Monteith equation (SCS, 1993). The grass reference crop evapotranspiration (ET_o) when multiplied by a crop coefficient (K_c) provides the estimate of long-term consumptive use of water by crops. To determine K_c, the basal crop coefficient, K_{cb}, is required. Basal crop coefficients for several crops and procedures for calculating K_{cb} are presented in this manual. The basal crop coefficients are available for all the major crops grown in the State of Texas.

This manual also contains a section on free-water evaporation for shallow ponds. The long-term estimates of free-water evaporation were made using the Borrelli-Sharif equation (Sharif et al., 1990) which was determined through statistical analysis to be the best equation for predicting free-water evaporation for shallow ponds. Data used to select the equation for estimating free-water evaporation came from reservoirs ranging in depth from 15 to 50 ft.

The following sections are contained in this manual:

Chapter 1—Introduction: Defines key terms and specifies the manual's contents.

Chapter 2—Measurement of Consumptive Use and Free-Water Evaporation: Provides information on how evapotranspiration and free-water evaporation are measured. Other sources of information about evapotranspiration are given.

ET Data

Chapter 3—Mean Consumptive Use for Agricultural Crops: Gives methodology for estimating mean crop consumptive use. Also included are contour maps of the grass reference crop evapotranspiration, ET_o. Mean crop consumptive use is presented for many of the major crops in Texas.

Chapter 4—Turfgrass: Presents consumptive use values for the common turfgrasses. Justification for the basal crop coefficients for the various turfgrasses is presented in this chapter.

Free Water Evaporation

Chapter 5—Free-Water Evaporation for Shallow Ponds: Discusses the methodology used to estimate free-water evaporation and provides contour maps for free-water evaporation for shallow ponds.

Chapter 6—Application of Consumptive Use Data: Includes examples of various water resources studies using consumptive use data.

Chapter 7—Auxiliary Information: Adds auxiliary information on water stress, salinity control, irrigation efficiency, and effective precipitation.

Appendix A—Glossary of Terms: Lists the terms and symbols used in this report.

Appendix B—Climatic Data: Illustrates contours of mean monthly values for minimum temperatures, wind run, average humidity, average temperature, minimum relative humidity, percent possible sunshine, and precipitation.

Chapter 2

Measurement of Consumptive Use and Free-Water Evaporation

In the planning of water resource systems and the allocation of water, it is important to know the actual consumptive use rates for crops and for other vegetation. To complete a water balance and to size storage facilities, it is necessary to know the actual free-water evaporation from water surfaces. The task of quantifying actual consumptive use is difficult because actual consumptive use may vary from zero to potential evapotranspiration for the crops or vegetation of concern depending on soil moisture conditions. Knowledge on availability of water, level of management, accurate climatic data, precise knowledge of the vegetation, and perfect models to predict evapotranspiration (ET) are generally lacking. To provide estimates of actual consumptive use, the general procedure is to assume "ideal conditions" and modify the values based on experience, logic, and knowledge of the problem.

Evapotranspiration

Definition of ET

Jensen (1983a) defined evapotranspiration as "the combined process by which water is transferred from the earth's surface to the atmosphere. It includes evaporation of liquid or solid water from the soil and plant surfaces plus transpiration of liquid water through plant tissue expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area." The above definition for evapotranspiration also fits the definition for "actual evapotranspiration" according to Jensen (1983b). Note that the term "consumptive use" is synonymous with the term "evapotranspiration."

Evapotranspiration varies spatially and temporally with time of year. Consequently, evapotranspiration must be measured or estimated over time and at many locations. It is impossible to measure evapotranspiration at all locations where it is needed. Therefore, estimates of evapotranspiration are developed using climatic factors. Climatological data on minimum and maximum temperature, wind speed, humidity or dew point temperature, and solar radiation or percent sunshine are used to estimate evapotranspiration.

Crops also are highly variable with respect to evapotranspiration rates. Not only are there a wide variety of crops, the evapotranspiration for a particular crop varies due to variety, management factors, growth stage, and general vitality of the plants (Nir and Finkel, 1982).

Reference Crop ET

To minimize the data collection and to provide a baseline for estimating evapotranspiration, the concept of reference crop evapotranspiration was developed (Doorenbos and Pruitt, 1977). Reference crop evapotranspiration equations were developed using climatic variables and calibrated with measured data for a selected crop. The reference crop is generally a well-watered cool-season grass (grass reference or ET_o), but well-watered alfalfa is also used as the reference crop (alfalfa reference or ET_r) (Wright, 1982). To estimate the evapotranspiration for crops other than the reference crop, crop coefficients are developed by using the following relationship (Jensen, 1983a):

Crop Coefficient

$$K_c = \frac{ET_{crop}}{ET_o} \qquad (1)$$

where

K_c = the crop coefficient incorporating the effects of crop growth stage, crop density, water stress, and other cultural and environmental factors affecting evapotranspiration
ET_{crop} = the evapotranspiration of the crop of concern (depth/time)
ET_o = the grass reference crop evapotranspiration (depth/time).

Numerous measurements of evapotranspiration for specific crops have been made in the U.S. and other countries. The K_c values for various crops have been summarized by Jensen (1974), Doorenbos and Pruitt (1977), Jensen et al. (1990), and SCS (1993).

Reference Crop Evapotranspiration

Reference crop evapotranspiration has been measured under research conditions and is used as a basis for estimating actual consumptive use of crops. There are two reference crop evapotranspiration methods used in the U.S.—grass reference (ET_o) and alfalfa reference (ET_r).

Throughout this manual the grass reference is used. The grass reference crop evapotranspiration (ET_o) is defined as the rate of evapotranspiration from an extensive surface (lengthy fetch) of 3 to 6 inches tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (Doorenbos and Pruitt, 1977). The grass is generally considered to be a cool-season (C3 metabolism) grass. The standard parameters used by SCS (1993) are 1) the height for the reference crop is 5 inches, 2) the surface resistance to vapor transport (r_c) is 1.22 days/mile, and 3) the albedo (α) is nominally 0.25.

The alfalfa reference crop evapotranspiration (ET_r) is defined as the rate of evapotranspiration that occurs under given climatic conditions for a field having a well-watered crop of alfalfa that is 12 to 18 inches in height, actively growing and completely shading the soil surface (Jensen, 1983a). Alfalfa reference crop evapotranspiration is most often used with the combination equation developed by Wright (1982) at Kimberly, Idaho.

Measurement of Consumptive Use

Historically the primary methods of measuring consumptive use or evapotranspiration have been by performing water balances in plots and by using lysimeters (Jensen et al., 1990). Very early attempts at quantifying consumptive use measured water use of crops grown in pots (Jensen, 1983b). These early measurements, while providing valuable insight into the phenomenon of evapotranspiration, have not produced usable data for field conditions. Most of the data used to develop current equations for estimating consumptive use have used data from lysimeters (Doorenbos and Pruitt, 1977; Jensen et al., 1990). During the last several years, technology has also allowed the use of the Bowen ratio method (Mohseni-Saravi et al., 1996), eddy correlation, and sap flow gauges (measures only the transpiration component) (Tolk et al., 1996) to measure evapotranspiration rates.

Lysimeters

Lysimeters are devices that hold a volume of soil that can be hydrologically isolated. The soil volume is placed in the lysimeter *in-situ* or in such a manner as to perform as an *in-situ* soil core after a period of settlement and acclimation, usually months. Water is added and removed as needed to maintain "well-watered conditions." Measurement of water use is determined using a simple water balance for the "water balance lysimeters" and by weighing the lysimeters for changes in weight for the more complex "weighing lysimeters." The highest quality data are generally obtained from weighing lysimeters with *in-situ* soil cores and with surface areas of approximately 97 ft^2. Regardless of the level of care given to the lysimeters, most researchers do not claim any greater accuracy than ± 5 percent for seasonal ET values even though some weighing lysimeters are capable of sensing the addition of a few drops of water on the lysimeter surface. Morgan and Lourence (1969) reported that the weighing lysimeters located at Davis, California have a sensitivity of 1/1000 of an inch or 0.5 pounds of water. Accuracy of measurement, however, also must take into consideration heat sinks, representation of vegetation in the lysimeter with the vegetation in the larger field, and other related factors.

The eddy correlation method measures the fluctuating vertical movements of air and humidity. While the average vertical velocity near the surface is zero, there can be a positive movement of moisture away from the surface. The eddy correlation technique measures fluctuations in temperature, wind speed, and humidity at time intervals of fractions of seconds. The integrated flux is determined and evapotranspiration calculated (Shuttleworth, 1993). Itier and Brunet (1996) stated that eddy correlation has become the standard measurement technique for evapotranspiration at the canopy scale (*in situ* within large fields).

Potential Evaporation

Potential evaporation is defined by Shuttleworth (1993) as "the quantity of water evaporated per unit area, per unit time from an idealized, extensive free water surface under existing atmospheric conditions." The above definition assumes meteorological conditions control the rate of evaporation. Van Bavel's (1966) definition of potential evaporation agrees with that of Shuttleworth (1993). When the surface of a crop or soil is wet or for evaporation from a free-water surface, there are no restrictions on the flow of water vapor except the energy available to evaporate water. This assumption appears valid for large lakes. In small bodies of water surrounded by dry soil and dry vegetation, some concern is necessitated about advective energy. The dry air gives up some of its heat thus increasing energy available for evaporation. This is the so-called "clothesline effect." The clothesline effect can also be observed for crop evapotranspiration from small irrigated fields in arid or semi-arid locations.

Measurement of Evaporation

Measurement of free-water evaporation is a very difficult task, and consequently there are few acceptable sets of data in the literature. If a lake is fed by a stream, the error in measuring the inflow and outflow generally masks the evaporation or creates great uncertainty in the evaporation measurements. To measure free-water evaporation, a pond or lake must be hydrologically isolated, or accurate measurements of inflow, outflow, and seepage rates are required to provide accurate estimates of evaporation. Consideration must also be given to factors such as the bias catch of precipitation in most rain gauges. For typical rain gauges, Linsely et al. (1975) reported a 10 percent deficiency in catch for a wind speed of 8 mph. Nevertheless, there are natural lakes and man made ponds and reservoirs where sufficient control of inflow and outflow exists to perform a water balance. Lake Hefner in Oklahoma is a good example where sufficient water flow control was available to obtain accurate measurements of evaporation rates (US Geological Survey, 1954). Lake Hefner, being an off-stream storage reservoir, was ideal for obtaining an accurate water budget (Crow et al., 1967).

Water Balance

On many lakes, an accurate estimate of evaporation can be determined by using an energy budget (Knapp, 1985). The energy budget can be expressed as:

$$Q_s + Q_a + Q_v - (Q_r + Q_{ar} + Q_{bs} + Q_e + Q_h + Q_w) = Q_o \qquad (2)$$

where

Q_a = incoming long-wave atmospheric radiation (cal/cm^2/day)
Q_{ar} = reflected atmospheric radiation (cal/cm^2/day)
Q_{bs} = long-wave radiation emitted by the body of water (cal/cm^2/day)
Q_e = energy used by evaporation (cal/cm^2/day)
Q_h = energy conducted by the body of water as sensible heat (cal/cm^2/day)
Q_o = change in energy stored in the body of water (cal/cm^2/day)
Q_r = reflected solar radiation (cal/cm^2/day)
Q_s = short-wave solar radiation incident to the water surface (cal/cm^2/day)
Q_v = net energy advected into the lake by inflow and withdrawal (cal/cm^2/day)
Q_w = energy advected in the evaporated water (cal/cm^2/day)

The above relationship was similar to the energy budget used at Lake Hefner (Allen, 1965).

Lake Hefner, with an area of approximately 2,600 acres, and a 0.28 acre pond near Lake Hefner had approximately equal annual evaporation. The primary difference in evaporation rates were their seasonal variations (Allen, 1965). This observation provides support for using climatic equations (such at the Penman-Monteith equation) to estimate annual evaporation when the climatic equations are calibrated with small experimental ponds. This relationship potentially provides a cost-effective system for calibrating climatic equations.

The accuracy of an energy budget to estimate evaporation appears of be ± 10 to 15 percent. The accuracy of water budgets may be greater, within ± 5 percent for small, highly controlled ponds.

Other Sources of Information

There are several excellent sources for evapotranspiration data and information on evapotranspiration processes. However, there are few sources for evaporation data. For evapotranspiration, the following references are recommended:

Soil Conservation Service. (1993). "Irrigation Water Requirements." *Part 623 National Engineering Handbook*, United States Department of Agriculture, Washington, D.C.

Important References

The procedures used to calculate evapotranspiration for this manual were taken from SCS (1993). It contains detailed procedures and all supporting documents for how to calculate evapotranspiration including crop coefficients. Also included in the SCS (1993) publication are detailed descriptions on irrigation efficiencies, leaching requirements, and on-farm and project irrigation requirements.

Jensen, M. E., R. D. Burman, and R. G. Allen. (1990). "Evapotranspiration and Irrigation Water Requirements," *ASCE Manual No. 70.*, American Society of Civil Engineers, New York, 332 pages.

The manual by Jensen et al. (1990) is a state-of-the-art manual on evapotranspiration. It contains detailed descriptions on how to use various procedures for estimating evapotranspiration, crop coefficients, use and evaluation of climatological data, and comparison of procedures for calculating evapotranspiration. It is an important reference in that it states that the Penman-Monteith procedure should be the standard for estimating evapotranspiration. It contains a wealth of background information on the general topic of evapotranspiration.

Doorenbos, J. and Pruitt, W. O. (1977). "Guidelines for Predicting Crop Water Requirements," FAO Irrigation and Drainage Paper No. 24, 2nd edition, FAO, Rome, Italy, 156 pages.

The FAO-24 Penman equation was considered by most practitioners to be the standard procedure for estimating evapotranspiration. The procedure is still widely used although it has been shown to overestimate evapotranspiration under a large variety of conditions (Itier and Brunet, 1996). It does contain information on ET_0 crop coefficients that are still widely used. The FAO has recently adopted the Penman-Monteith method for estimating evapotranspiration. A review of SCS (1993) reveals that

SCS (1993) used the crop coefficients developed by Doorenbos and Pruitt (1977), but that they are used as basal crop coefficients (K_{cb}). It is important to note that Doorenbos and Pruitt's (1977) contains crop coefficients for free-water surfaces and for free-water surfaces covered with floating vegetation. These crop coefficients are for shallow ponds—less than 17 ft in depth.

American Society of Agricultural Engineers. (1985). "Advances in Evapotranspiration," Proceedings of the National Conference in Evapotranspiration, Chicago, Illinois. 453 pages.

The proceedings from this conference provide background information on the use of lysimeters, development of crop coefficients, advances in theory, and application of evapotranspiration to hydrology and irrigation management.

Camp, C. R., and E. J. Sadler, and R. E. Yoder. (1996). "Evapotranspiration and Irrigation Scheduling," Proceedings of the International Conference. American Society of Agricultural Engineers, St. Joseph, Michigan. 1165 pages.

This text contains the proceedings from the latest conference on evapotranspiration. It provides insight into the latest technologies for measuring and procedures for estimating evapotranspiration. Several papers provide information on crop coefficients.

Chapter 3

Mean Consumptive Use for Agricultural Crops

The estimation of crop evapotranspiration (ET_{crop}) first requires the determination of grass reference crop evapotranspiration (ET_o) and then a crop coefficient (K_c). The three variables are related by the following relationship:

Crop ET

$$ET_{crop} = K_c ET_o \tag{3}$$

where

ET_{crop} = the estimated crop evapotranspiration (depth/time)
K_c = grass reference crop coefficient (dimensionless)
ET_o = grass reference crop evapotranspiration (depth/time)

The grass crop coefficient, K_c, is a dimensionless coefficient that changes with time as a function of the crop's growth stage, soil moisture condition, and wet soil surface evaporation (Wright, 1981). In this case, K_c values must be developed using basal crop coefficients (K_{cb}) for the grass reference crops if used with the grass reference crop evapotranspiration, ET_o. As stated above, ET_o is defined as the rate of evapotranspiration from an extensive surface (lengthy fetch) of 3 to 6 inches tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (Doorenbos and Pruitt, 1977). The grass used to define ET_o is a cool-season grass. If procedures are accurately followed for estimating ET_{crop}, the degree of accuracy should be ± 10 percent (Wright, 1981).

Grass Reference Crop Evapotranspiration

For this particular manual, ET_o is calculated using the Penman-Monteith procedure (SCS, 1993). As stated in the previous section of this manual, the Penman-Monteith procedure is recommended and ranked first among the various procedures for estimating ET_o tested by Jensen et al. (1990). The Penman-Monteith equation is as follows:

Penman-Monteith Equation

$$ET_o = \left(\frac{1}{\lambda}\right)\left[\left(\frac{\Delta}{\Delta+\gamma^*}\right)(R_n - G) + \left(\frac{\gamma}{\Delta+\gamma^*}\right)\left(0.622\frac{K_1\lambda\rho}{BP}\right)\frac{(e_z^o - e_z)}{r_a}\right] \tag{4}$$

where

ET_o = grass reference crop evapotranspiration (in./day)
λ = heat of vaporization of water (lang/in)
Δ = slope of vapor pressure curve (mb/deg F)
γ = psychrometric constant (mb/deg F)
$\gamma*$ = adjusted psychrometric constant = $\gamma(1+r_c/r_a)$ (mb/deg F)
R_n = net radiation (lang/day)
G = soil heat flux (lang/day)
K_1 = unit conversion constant for Penman-Monteith equation
ρ = density of air (lb/ft^3)
BP = barometric pressure (mb)
r_a = aerodynamic resistance to sensible heat and vapor transfer (day/mi)
r_c = surface resistance to vapor transport, i.e., the canopy resistance (day/mi)
e_z^o = average saturated vapor pressure at height z above the surface (mb)
e_z = actual vapor pressure at height z above the soil surface (mb)

The procedures used to calculate or determine the values of the variables in Equation 4 were taken from SCS (1993). An example of the procedures used to make the calculations is located at the end of this chapter (page 99). The example is a copy of a MathCAD® program output used to validate the calculation procedures.

Contour Maps of Mean ET_o

For the stations shown in Figures 1 and 2, ET_o was calculated using the Penman-Monteith procedure (Equation 4). The calculated daily values were summed to obtain values for the month. Monthly values were averaged over a period of years to obtain the mean monthly values. The mean monthly ET_o values were then plotted and contours drawn covering the State of Texas (Figures 10 through 21). ET_o values for various locations in Texas are presented in Table 5, while estimates of ET_o are available for any location in the State of Texas by using the contour maps.

Climatic Data

To calculate ET_o, the Penman-Monteith procedure requires the following data:

Temperature
Wind run
Humidity or dew point temperature
Solar radiation or percent sunshine

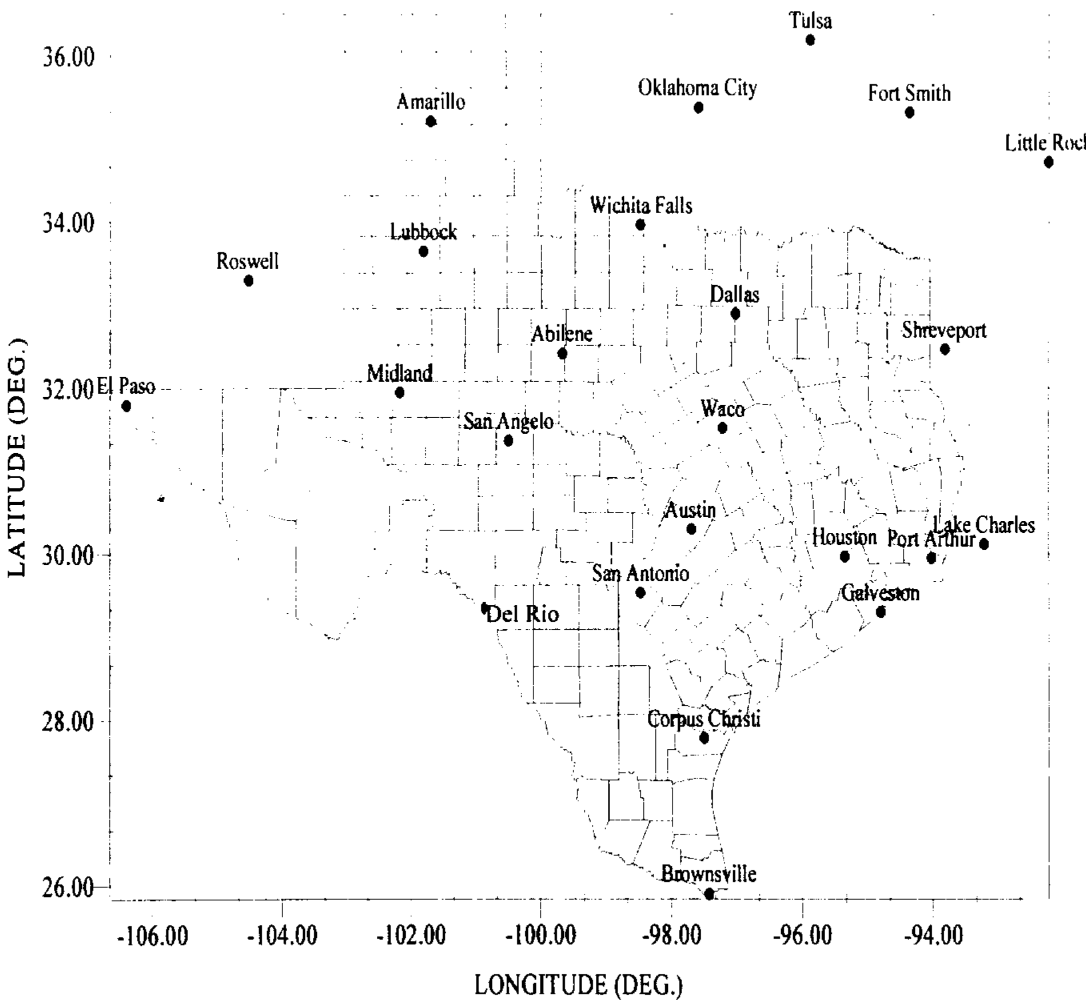


Figure 1.-Climatic Stations Containing Temperature, Humidity, Wind, Percent Sunshine, and Precipitation.

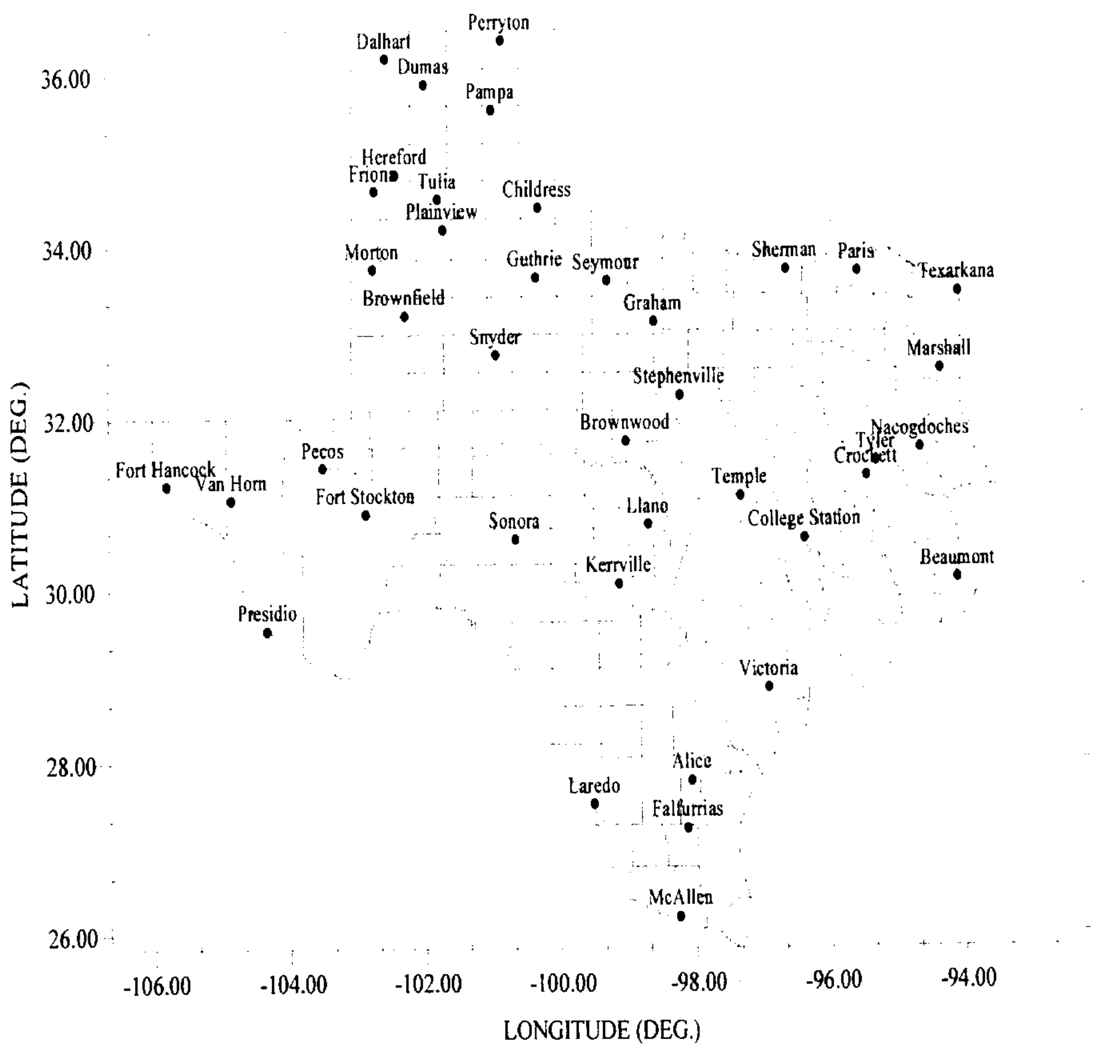


Figure 2.-Climatic Stations Having Temperature and Precipitation.

This information was obtained from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service records for locations in Texas and selected locations in New Mexico, Oklahoma, Arkansas, and Louisiana (Figure 1).

To provide for locations in all parts of Texas where ET_0 values were desired, stations that have only temperature and precipitation data were used (Figure 2). A study was performed to determine if ET_0 could be accurately estimated using daily temperature data and monthly average values for humidity, wind run, and percent sunshine. The results from the study demonstrated that mean ET_0 estimates were as accurate using the monthly average values for humidity, wind run, and percent sunshine as the ET_0 calculated using the daily values for all variables at the same site. A linear correlation equation determined for the measured versus predicted data had a slope of 1.00 and an intercept of a few thousandths of an inch. A plot of the ET_0 calculated with daily values versus using monthly averages for wind, humidity, and percent sunshine is shown in Figure 3. It was concluded that monthly average values for humidity, wind run, and percent sunshine could be used without any significant decrease in accuracy in estimating mean values of ET_0.

The stations with complete climatic data sets are strategically spaced throughout the State of Texas. Climatic stations were also used in New Mexico, Oklahoma, Arkansas, and Louisiana to allow contours to be drawn for all parts of Texas without extrapolation of contours through areas without data.

Cumulative Frequency for ET_0

For various purposes, such as determining the hydraulic capacity of an irrigation system, the maximum ET_{crop} may be needed. To aid in this determination, cumulative frequencies of ET_0 values were developed for several strategic locations in Texas and for Shreveport, Louisiana. The user can determine the percent time a given ET_0 value will be above or below the mean ET_0 value for a given month. Note that according to Equation 3, ET_{crop} is the product of K_c times ET_0. Thus, ET_{crop} would change proportionally according to changes in ET_0. The cumulative frequency curves are at the end of this Chapter in Figures 22 - 28.

Crop Coefficients

The main purpose of this manual is to provide estimates of mean-annual consumptive use rates for crops in the State of Texas. Estimation

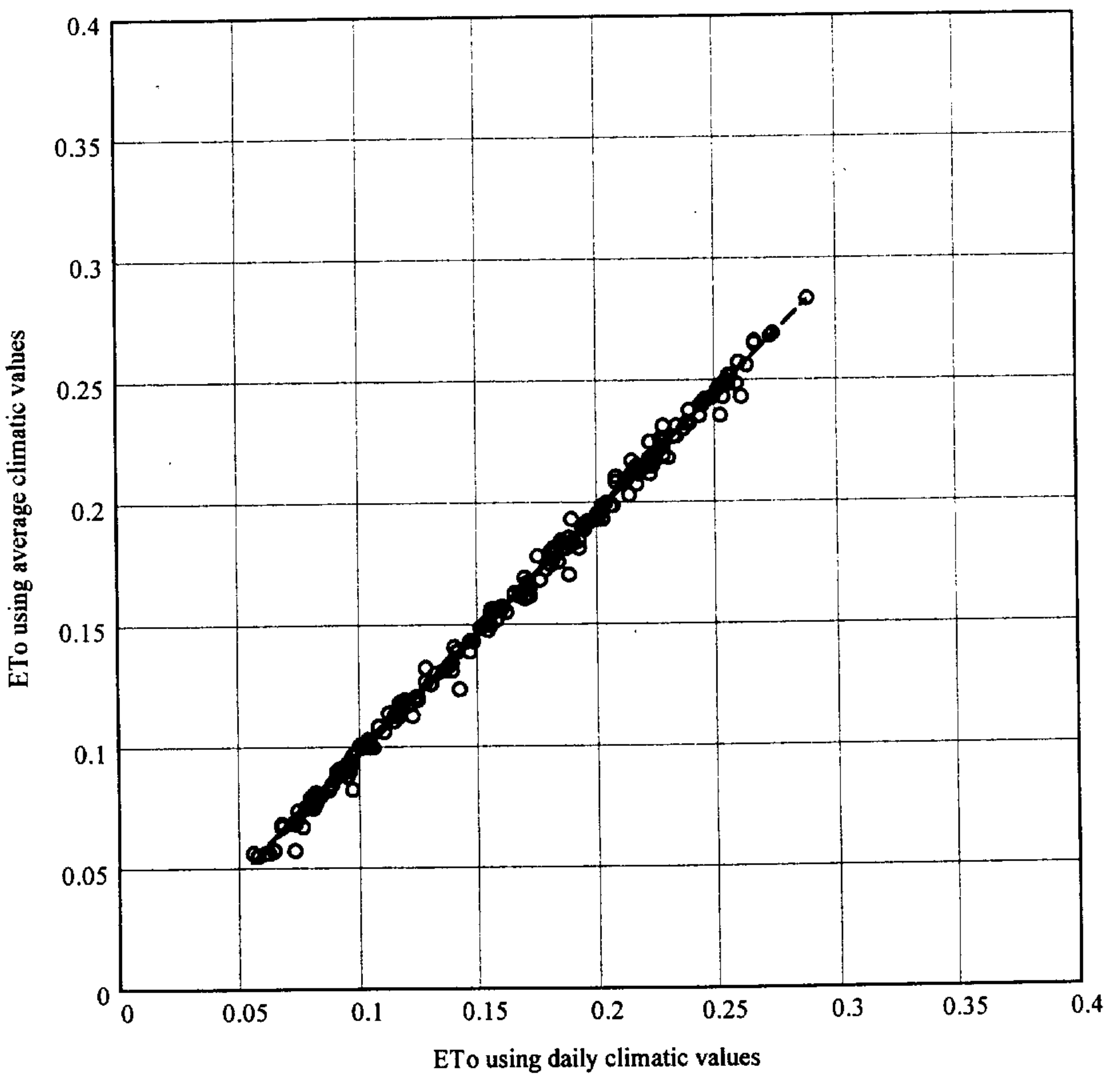


Figure 3. Et_0 calculated using daily values for humidity, wind, and percent sunshine versus Eto calculated using average values for humidity, wind, and percent sunshine.

of the mean-annual consumptive use requires the use of crop coefficients as shown in Equation 3. Crop coefficients, as stated in Chapter II of this manual, are determined from lysimeter studies and can be spatially applied to other locations. A crop coefficient is determined by rearranging the terms in Equation 3 and has the following general relationship:

$$K_c = \frac{ET_{crop}}{ET_o} \qquad (5)$$

where

K_c = the grass reference crop coefficient for a particular crop
ET_{crop} = the measured consumptive use for the particular crop (depth/time)
ET_o = the grass reference crop evapotranspiration (depth/time).

In practice, K_c must take into consideration factors such as wet soil, stress due to a lack of soil moisture, crop maturity, wind, and relative humidity. For this manual, it is assumed that the crop has adequate soil moisture for maximum growth. However, all other factors must be taken into consideration in estimating K_c for a particular crop.

The crop coefficient, K_c, is related to the above factors by the general relationship:

Crop Coefficient

$$K_c = K_{cb} \times K_s + K_w \qquad (6)$$

where

K_c = the crop coefficient for a particular crop
K_{cb} = the basal crop coefficient for the particular crop
K_s = the factor related to water stress
K_w = factor to account for the increased evaporation from wet soils following a rain or irrigation event.

As stated earlier, for the purposes of this manual, stress due to the lack of soil moisture is ignored, or K_s is set equal to 1. If needed, it can be taken into consideration (see Chapter 7). The factor K_w varies with soil type and with the number of times wet surfaces are developed on a crop. The effect of adding the wetness factor to K_{cb} is illustrated in Figure 4.

The basal crop coefficients, K_{cb}, used in this manual are for grass reference crop evapotranspiration, ET_o. The coefficients are published in SCS (1993) and Jensen et al. (1990) manuals on consumptive use of crops.

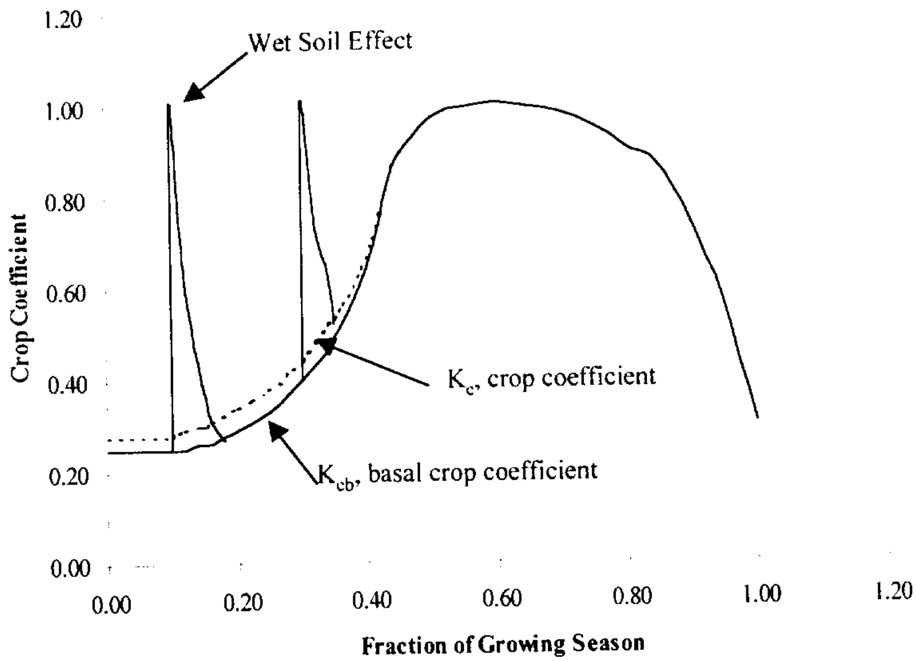


Figure 4.-Generalized Crop Coefficient Curve

Calculation of Basal Crop Coefficient (K_{cb})

The K_{cb} values used herein were adapted from SCS (1993) and are listed in Tables 6 - 12 at the end of this chapter. Note that the K_c values found in Doorenbos and Pruitt (1977) were used as K_{cb} values in SCS (1993). The K_c values include an average soil wetness for irrigated crops whereas K_{cb} assumes the soil surface is dry. Remember that the FAO 24 Penman procedure (Doorenbos and Pruitt, 1977), in general, estimates a greater ET_o than does the SCS (1993) Penman-Monteith procedure.

Growing Season and Planting Date

The first step in developing the K_{cb} curve for a crop is to determine the growing season of the crop. This is a task that is not to be taken lightly. Each percentage point error in determining the length of the growing season will result in approximately a percentage point error in estimating ET_{crop}. The task is compounded by the fact that the same crop grown side-by-side may be managed differently and thus effectively have different lengths of growing season. The variation in growing season can be seen by evaluating the times when crops are planted and harvested as reported by the Texas Agricultural Statistics Service (1991). Variation of 10 percent or more within any one crop reporting district is common.

Definition: Growing Season

The growing seasons for the major crops grown in Texas and the planting dates as reported by the Texas Agricultural Statistics Service for the years 1990, 1991, and 1992 are presented in Table 13 at the end of this chapter. The growing season was assumed to be the time between when 50 percent of the crop was planted and when 50 percent of the crop was harvested (except cotton). The planting date is assumed to be the date when 50 percent of crops within a crop reporting district were planted. The planting date will affect the length of the growing season as well as the rate of crop development to full ground cover and onset of maturity (Doorenbos and Pruitt, 1977). The boundaries of the various crop reporting districts in Texas are shown in Figure 5. In addition, the SCS (1993) provides the range of days for the growing seasons of most crops grown in Texas (Table 6). They do not, however, provide a planting date.

For local information on the growing season of crops, one should consult the local county agricultural extension agent. Another valuable source of information are the Texas A&M University Research & Extension Centers whose addresses and telephone numbers are given in Appendix B.

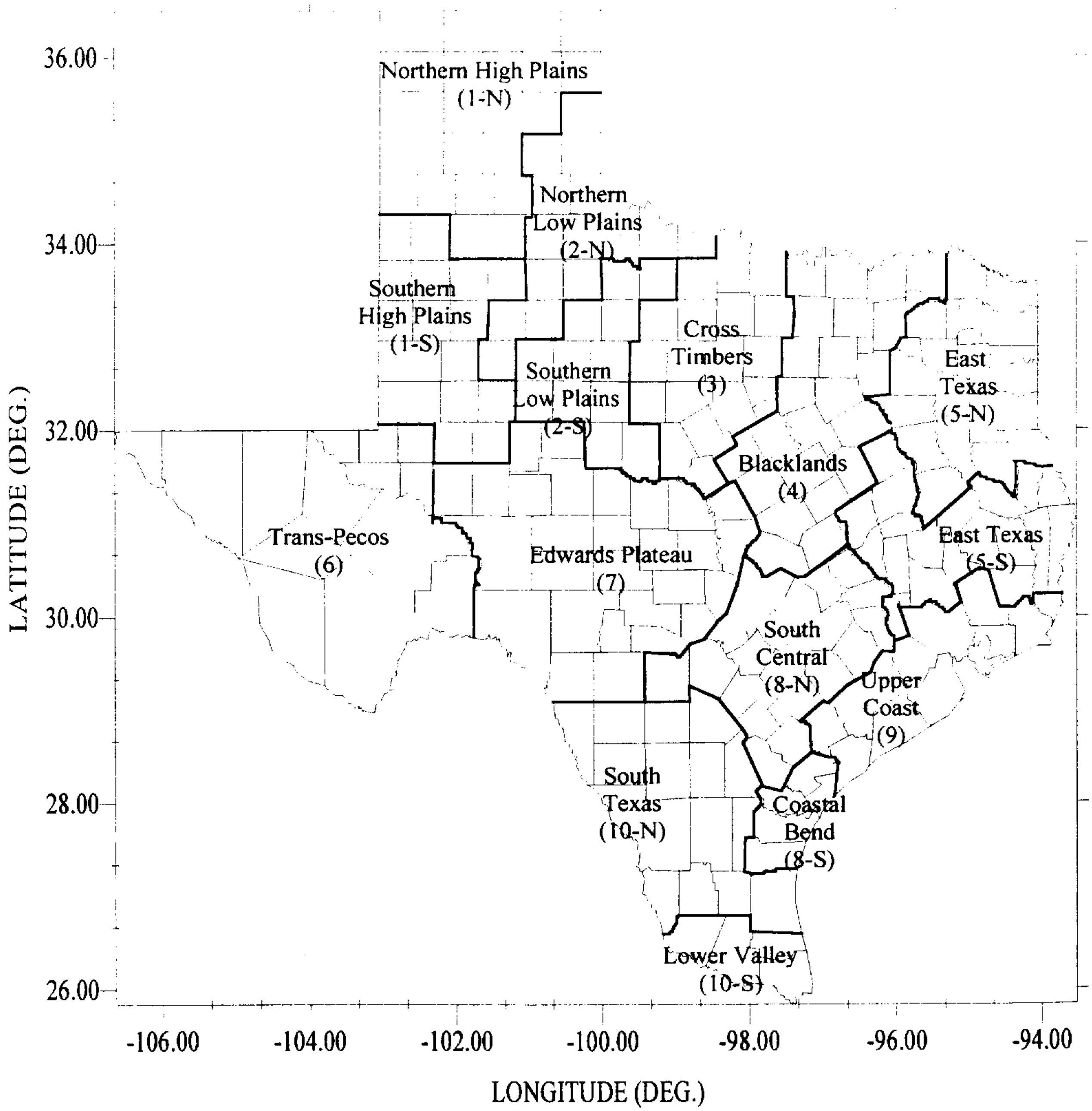


Figure 5.-Texas Crop Reporting Districts.

Determining Crop Growth Stages

A definition sketch for the K_{cb} curve is shown in Figure 6. The growing season is divided into four stages: 1) initial, 2) canopy development, 3) mid-season, and 4) maturation. The length of each stage can be determined by using the terms F_{S1}, F_{S2}, and F_{S3} as given in Table 6 for each particular crop. The term F_{S1} is the fraction of the growing season to the start of the canopy development stage; F_{S2} is the fraction of the growing season to the start of the mid-season stage; and F_{S3} is the fraction of the growing season to the start of the maturation stage. Given the length of the growing season and the planting date, the beginning and ending date for each stage of the growing season can be determined.

Example 1: Dates for Growth Stages during Growing Season

Soybeans Crop Reporting District 7 (Kerrville)
Planting Date = May 10th Growing season = 140 days
$F_{S1} = 0.15$ $F_{S2} = 0.37$ $F_{S3} = 0.81$

Growth Stages

Start of Canopy Development = Planting Date + F_{S1} × Growing Season
Start of Canopy Development = May 10th + (0.15) × (140) = May 31st

Start of Mid-Season = Planting Date + F_{S2} × Growing Season
Start of Mid-Season = May 10th + (0.37) × (140) = July 1st

Start of Maturation = Planting Date + F_{S3} × Growing Season
Start of Maturation = May 10th + (0.81) × (140) = Aug 31st

Harvest Date = Planting Date + Growing Season
Harvest Date = May 10th + 140 = Sep 27th

Selection of K_{cb} for Wind

After the length of the growing season is determined and the planting date established, development of the K_{cb} curve can begin. There are three (3) points on the K_{cb} curve that should be noted. First is the K_{cb} value for initial stage that is set by SCS (1993) at 0.25 and does not change. Second is the K_{cb} value for the start of the mid-season stage that is listed in Table 6 as K_{cp}. Third is the K_{cb} value for the end of the maturation stage that is listed in Table 6 as K_{cm}.

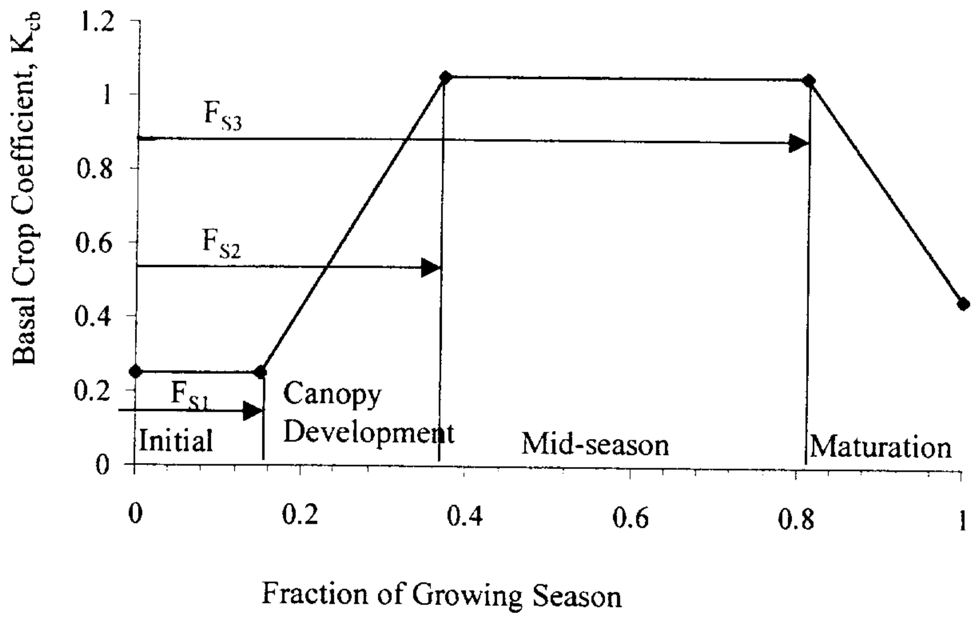


Figure 6.-Definition Sketch for Stages of Growth

A check of Table 6 indicates that K_{cb} is a function of mean minimum relative humidity and strength of wind. Contours of mean minimum relative humidity (Figure B1) and mean wind runs (Figure B2) are given for each month in Appendix B. All parts of the State have a wind run less than 250 miles/day except for the extreme northern Panhandle during the months of March and April. Thus, for all other locations in Texas, coefficients for moderate wind run should be used.

Adjusting K_{cb} for Wind

If the mean wind run is less than or equal to 250 miles/day (see wind run contours, Figure B2 in Appendix B), then select the K_{cp} and the K_{cm} values from the "Moderate Wind" column of Table 6. Use the "Strong Wind" values if the wind run is greater than 250 miles/day. There is no interpolation between values to adjust for various wind run values.

Adjustment of K_{cb} for Minimum Relative Humidity

The next step is to adjust the K_{cp} and K_{cm} values for relative humidity. These values will need to be adjusted or interpolated for relative humidity, if necessary, between the values given for humid and arid conditions using the minimum relative humidity for the appropriate dates.

The general procedure for adjusting K_{cp} and K_{cm} are as follows:

1. Determine the date for the start of the mid-season stage.
2. Determine the date for the start of the maturation stage.
3. Determine K_{cp} and K_{cm} from Table 6.
4. Determine the mean monthly minimum relative humidities for the dates corresponding to the start of the mid-season stage and the maturation stage.
5. If the mean monthly minimum relative humidity for the period representing K_{cp} is less than 20 percent ($Rh_{min} \leq 20$ percent) or it is greater than 70 percent ($Rh_{min} \geq 70$ percent), then use K_{cp} as given in Table 6.
6. If the mean monthly minimum relative humidity is greater than 20 percent but less than 70 percent ($70 > Rh_{min} > 20$) then make the following adjustment to K_{cp}:

$$K_{cp} = K_{cp\_humid} + \left(K_{cp\_arid} - K_{cp\_humid}\right) \times \left(\frac{70 - Rh_{min}}{50}\right) \quad (7)$$

for $(70 > Rh_{min} > 20)$

7. If the mean monthly minimum relative humidity for the period representing K_{cm} is less than 20 percent ($Rh_{min} \leq 20$ percent) or it is

greater than 70 percent ($Rh_{min} \geq 70$ percent), then use K_{cm} as given in Table 6.

8. If the mean monthly minimum relative humidity is greater than 20 percent but less than 70 percent ($70 > Rh_{min} > 20$), then make the following adjustment to K_{cm}:

$$K_{cm} = K_{cm\_humid} + \left(K_{cm\_arid} - K_{cm\_humid}\right) \times \left(\frac{70 - Rh_{min}}{50}\right) \qquad (8)$$

9. Plot the K_{cb} curve as shown in Figure 7.

Example 1 (continued): Adjustment of K_{cp} and K_{cm}

Kerrville: $K_{cp\_humid} = 1.00$ $K_{cp\_arid} = 1.10$

Rh_{min} for start of mid-season stage (July 1st) is 44 percent.

$$K_{cp} = K_{cp\_humid} + \left(K_{cp\_arid} - K_{cp\_humid}\right) \times \left(\frac{70 - Rh_{min}}{50}\right)$$

$$K_{cp} = 1.00 + (1.10 - 1.00) \times \left(\frac{70 - 44}{50}\right) = 1.05 \qquad (7)$$

for $(70 > Rh_{min} > 20)$

$K_{cm\_humid} = 0.45$ $K_{cm\_arid} = 0.45$

K_{cm} is the same for climate condition of arid and humid, thus $K_{cm} = 0.45$

At this point, all the information is available to plot the K_{cb} curve. The K_{cb} curve for the above example is shown in Figure 7.

Average K_{cb} Values for Each Month

To determine the average K_{cb} values for each month, the first step is to plot the K_{cb} for the growing season as adjusted above for wind and relative humidity. Second, divide the curve into the calendar months. Third, calculate the average K_{cb} for each calendar month. If a month has just a portion of the crop growing season, calculate the average K_{cb} for that portion of the month covered by the crop growing season. Shown in Figure 7 is the K_{cb} curve generated for Example 1. The average K_{cb} values are shown for each calendar month.

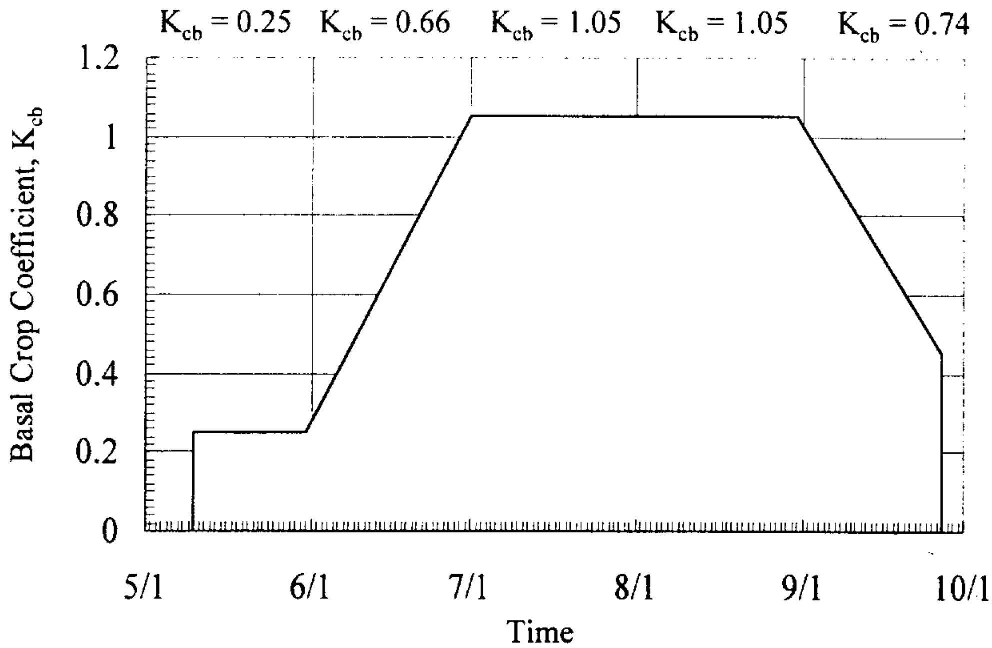


Figure 7.-Basal Crop Coefficient Curve for Example 1.

Wet Soil Evaporation Factor (K_w)

The wet soil evaporation factor, K_w, that is used only as long as the basal crop coefficient is less than one. It was defined by Wright (1981) as:

$$K_w = (1 - K_{cb})\left[1 - \left(\frac{t}{t_d}\right)^{0.5}\right](F_w) \tag{9}$$

Adjustment For Wet Soil

where

K_w = factor to account for the increased evaporation from wet soils (daily value)
K_{cb} = basal crop coefficient if less than 1.0
t = elapsed time since wetting, days
t_d = time required for the soil surface to dry, days
F_w = the relative portion of the soil surface originally wetted

The time required for the soil surface to dry, t_d, is a function of the soil texture. The t_d values for various soils and the evaporation decay function for the soils are given in Table 1 (SCS, 1993). Table 1 was adapted from SCS (1993). As an example, the wet soil surface decay function for a clay loam soil is illustrated in Figure 8. Figure 9 provides an example for multiple wet events in a single month.

Determination of Wet Soil Evaporation Events

When estimating mean consumptive use, it is difficult to determine how often the soil surface is wetted by precipitation and irrigation events. To provide an estimate for the number of precipitation events per month, the mean monthly frequencies for precipitation greater than 0.1 inches are presented in Table 14. The 0.1 inch precipitation was selected as a compromise for the threshold depth of precipitation to consider when precipitation-generated wet soil evaporation events occur. For precipitation depths less than 0.1 inches, the moisture will evaporate and will represent only a small fraction of the ET_{crop} for the day. When the precipitation event is greater than 0.1 inches, but less than the ET_{crop} for the day, some over-estimation of ET_{crop} will occur. The 0.1 inch threshold for precipitation events appears to provide a balance between over and under estimation of wet soil evaporation.

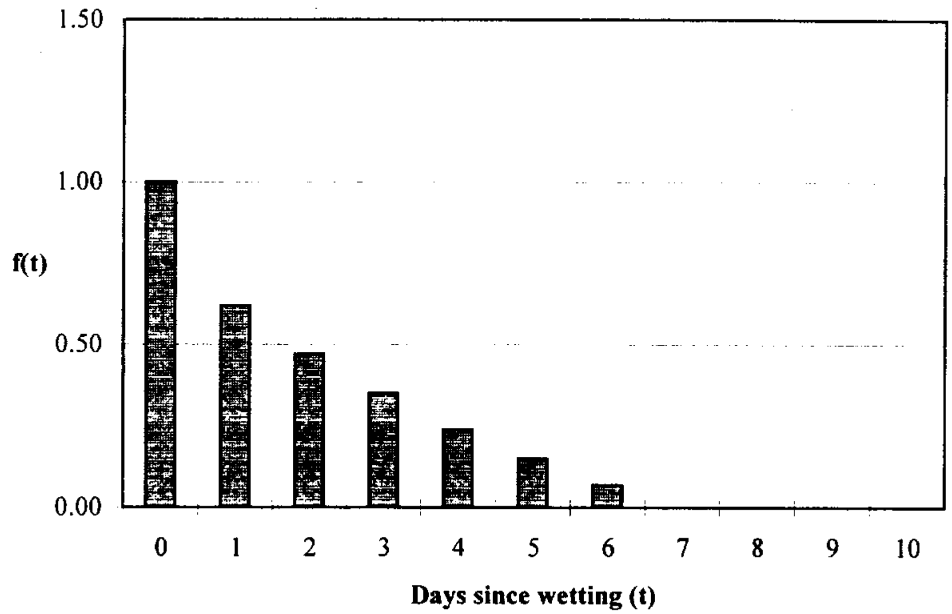


Figure 8.-Wet Soil Surface Evaporation Decay Function f(t) for Clay Loam Soil (adapted from SCS, 1993).

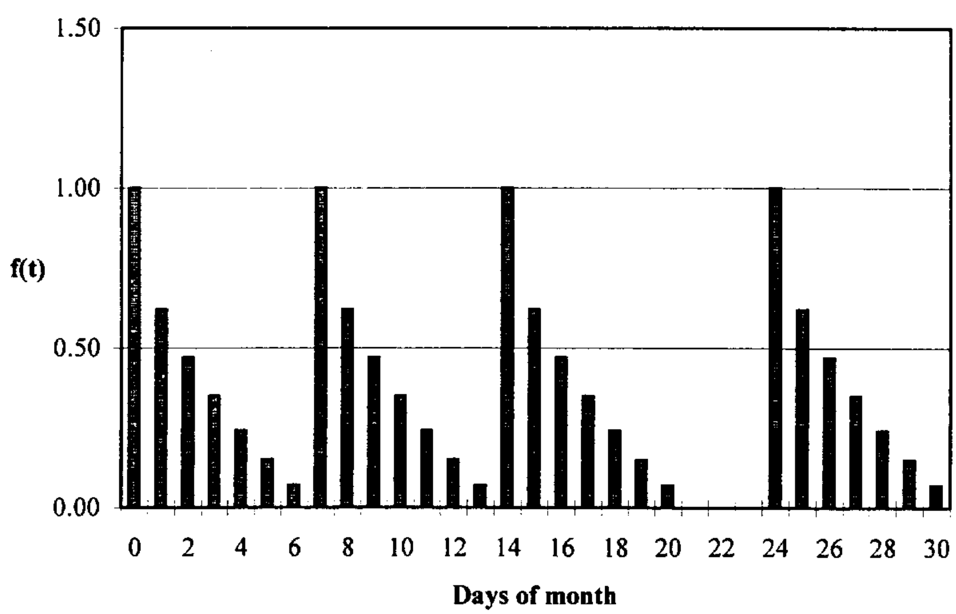


Figure 9.-Wet Soil Surface Evaporation Decay for Clay Loam Soil for Multiple Precipitation Events During a Month.

Determination of K_w

The K_w calculated using Equation 9 provides K_w for a single day. In this manual, ET_{crop} is calculated on a monthly basis. The effect of wetness must be taken into consideration for the entire month. This was accomplished by determining the frequency of precipitation greater than 0.1 inches, by obtaining a statistical count of the number of days the soil will remain wet, and estimating the degree of wetness as estimated using the wet soil surface evaporation decay function presented in Table 1. The following relationships define the use of K_w:

$$ET_{crop\_mon} = ET_o \times K_{cb} \times K_s + ET_o \times K_w \qquad (10)$$

$$ET_{crop\_mon} = ET_o \times K_{cb} \times K_s + ET_o(1 - K_{cb}) \sum_{j=1}^{wet\_events} \sum_{t=0}^{t_d} \left[1 - \left(\frac{t}{t_d}\right)^{0.5}\right] F_w \qquad (11)$$

for $K_{cb} < 1.0$

If t_d is greater than (30/wet_events), then t_d is equal to (30/wet_events).

For $K_{cb} \geq 1.0$ the following equation is used:

$$ET_{crop\_mon} = ET_o \times K_{cb} \times K_s \qquad (12)$$

where

ET_{crop_mon} = crop evapotranspiration for a given month (in./mon)
ET_o = the grass reference crop evapotranspiration for a given month (in./mon)
F_w = the relative portion of the soil surface originally wet
K_{cb} = estimated basal crop coefficient for the particular month
K_w = factor to account for the increased evaporation from wet soils
t = elapsed time since wetting (days)
t_d = time required for the soil surface to dry (days) (Table 1)
wet_events = estimated number of precipitation and irrigation wetting events for the month.

Equation 11 is to be used when K_{cb} is less than 1.0, and Equation 12 is to be used when $K_{cb} \geq 1.0$. The wetting events are assumed to wet the entire surface, thus F_w is set at 1.0. The number of events and the number of days proceeding a wetting event were determined as a function of the sum of precipitation frequency and estimated number of irrigation events. This allowed for a new term called a wetting factor, WF. The term WF was determined for six (6) soil textures and is presented in Table 15. Equation 10 can then be rewritten as:

$$ET_{crop\_mon} = ET_o \times K_{cb} \times K_s + ET_o(1 - K_{cb}) \times WF \times F_w \tag{13}$$

with

Wetting Factor

$$WF = \sum_{j=1}^{wet\_events} \sum_{t=0}^{t_d} \left[1 - \left(\frac{t}{t_d} \right)^{0.5} \right] \tag{14}$$

$$K_w = (1 - K_{cb}) \times WF \times F_w \qquad \text{for } K_{cb} < 1.0 \tag{15}$$

and $K_w = 0$ for $K_{cb} \geq 1$.

where

ET_{crop_mon} = crop evapotranspiration for a given month (in./mon)
ET_o = the grass reference crop evapotranspiration for a given month (in./mon)
K_{cb} = estimated basal crop coefficient for the particular month
K_w = factor to account for the increased evaporation from wet soils
t = elapsed time since wetting (days)
t_d = time required for the soil surface to dry (days) (Table 1)
F_w = the relative portion of the soil surface originally wet.
wet_events = estimated number of precipitation and irrigation wetting events for the month.
WF = wetting factor (Table 15)

Consideration of Irrigation Events

Irrigation of a crop can be accomplished with several different types of irrigation systems. Each irrigation system may have a different wetting pattern resulting in a different relative portion of the soil surface being wetted, F_w. The F_w values for the most common type of irrigation systems are presented in Table 2. On the other hand, precipitation events will wet 100 percent of the surface or have a F_w equal to 1.0. The users will have to determine for their particular cases what would be the average F_w for the combination of irrigation and precipitation events. Because this manual is concerned with long term mean ET_{crop} rates, F_w equal to 1.0 is recommended unless irrigation events are the predominant type of events and, of course, the type of irrigation system is a system with a F_w less than 1.0.

Table 1.-Wet Soil Surface Evaporation Decay Function f(t)[1] and the Persistence Factor P_f[2] for Typical Soils (from National Engineering Handbook 1993).

Time since wetting (t), days[3]	Clay	Clay loam	Silt loam	Sandy loam	Loamy sand	Sand
	Drying time (t_d) in days					
	10	7	5	4	3	2
0	1.00	1.00	1.00	1.00	1.00	1.00
1	0.68	0.62	0.55	0.50	0.42	0.29
2	0.55	0.47	0.37	0.29	0.18	0.00
3	0.45	0.35	0.23	0.13	0.00	
4	0.37	0.24	0.11	0.00		
5	0.29	0.15	0.00			
6	0.23	0.07				
7	0.16	0.00				
8	0.11					
9	0.05					
10	0.00					
----	----	----	----	----	----	----
P_f	3.89	2.90	2.26	1.92	1.60	1.29

1. f(t) = wet soil evaporation decay function = $1 - \sqrt{\frac{t}{t_d}}$

2. P_f = wet soil persistence factor = $\sum_{t=0}^{t_d} f(t)$

3. t = 0 represents the day of wetting, and 1 is one day after wetting.

Table 2.-Fraction of the Soil Surface Wetted for Various Types of Irrigation (from National Engineering Handbook 1993).

Method	**Fw**
Rain	1.00
Above canopy sprinklers	1.00
LEPA systems (every other row)	0.50
Borders and basin irrigation	1.00
Furrow irrigation	
Large application depth	1.00
Small application depth	0.50
Every other row irrigated	0.50
Trickle irrigation	0.25

The user should add the expected precipitation events (Table 14) to the estimate of the number of irrigation events per month. A good estimate for irrigated agriculture is 2 or 3 irrigation events for surface irrigation systems and 3 to 6 irrigation events for sprinkler systems. Once the total number of wetting events is estimated, then the WF can be determined from Table 15 for the particular month and particular soil texture.

Calculation of K_w for Example 1

Using the information developed above and the tables provided at the end of this chapter, K_w can be determined. The following table contains the basic information:

Table 3. Data for Determination of K_w

Month	K_{cb}	Precipitation Frequency	Wetness Factor (WF)	K_w
May * (10 - 31)	0.25**	8.08#	0.63##	0.472+
June	0.66	7.85	0.62	0.211
July	1.05	6.23	0.55	0
August	1.05	5.62	0.51	0
September (1 - 27)	0.74	6.15	0.54	0.141

* Growing season is from May 10th to September 27th.
** Taken from Figure 7.
\# Values obtained from Table 14 for Kerrville plus 2 irrigation events for each month except September. No irrigation events were assumed for September.
\## Values obtained from Table 15.
\+ Calculated using Equation 15. The variable F_w is assumed to be 1.0.

Calculation of ET_{crop} for Example 1:

All the information is now available to calculate ET_{crop} using Equation 10. The following table is used to calculate ET_{crop}:

Table 4. Determination of ET_{crop}

Month	ET_o (inches)	K_{cb}	K_w	Fraction of month in growing season	ET_{crop} (inches)
May * (10 - 31)	6.18**	0.25***	0.472#	22/31=0.71	3.17##
June	6.96	0.66	0.211	1.0	6.06
July	7.96	1.05	0	1.0	8.36
August	7.74	1.05	0	1.0	8.13
September (1 - 27)	6.15	0.74	0.140	27/30=0.90	4.87
Total					30.59

* Growing season is from May 10th to September 27th.
** Values obtained from Figures 14 - 18.
*** Taken from Figure 7.
\# Determined in Table 3.
\## Calculated using Equation 10. K_s is assumed to be 1.0.

Presented at the end of this chapter (page 89) is a complete set of calculations for Example 1 presented as a whole rather than in several parts. Also presented at the end this chapter (page 94) is a second example on how to calculate ET_{crop} for a specific crop.

ET_{crop} for Alfalfa

Presented at the end of this chapter are contour maps of mean monthly ET_{crop} for alfalfa (Figure 30). Alfalfa is particularly suited for the sunny and dry climate and responds well to irrigation. It is found throughout the State of Texas and is in all crop reporting districts (see Figure 5). Alfalfa is often used as a reference crop to compare potential yield for different locations, soils, precipitation, and irrigation amounts.

ET_{crop} for Major Texas Crops

Mean annual crop evapotranspiration rates are estimated for several crops at various locations and are presented in Table 16. The ET_{crop} estimates were made for a clay loam soil and using the growing seasons and dates of planting for the crops shown in Table 13.

Non-cropped or Bare Soils Evaporation

One often needs to estimate evaporation water losses from bare soil during the period between actively growing crops (the non-cropped or non-growing season). Doorenbos and Pruitt (1977) developed a procedure to make these estimates based on ET_o and the frequency of significant precipitation events or irrigations. To eliminate the use of a table, the SCS (1993) developed two equations that estimate an average crop coefficient, K_c, for the non-cropped period. The equations are:

when $f_p < 4$ days

$$K_c = (1.286 - 0.27 f_p) e^{\{(0.254 - 1.07 \ln(f_p) ET_o)\}} \qquad (16)$$

when $f_p \geq 4$ days

$$K_c = 2 f_p^{-0.49} e^{\{(-0.51 - 1.02 \ln(f_p)) ET_o\}} \qquad (17)$$

where

K_c = average crop coefficient during the period
f_p = interval between significant rains or irrigations (days)
ET_o = average grass reference crop evapotranspiration for the period (in./mon).

Non-cropped Period Water Use

The value for f_p can be estimated by dividing the number days of the month by the number of precipitation events presented in Table 14. To determine the values for ET_o, use Table 5 or Figures 10 - 21. The water loss due to evaporation for the bare soil during the non-cropped period is:

$$E_{soil} = K_c ET_0$$

where

E_{soil} = the water loss due to evaporation during the non-cropped period (in./mon)
K_c = average crop coefficient during the period
ET_o = average grass reference crop evapotranspiration for the period (in./mon).

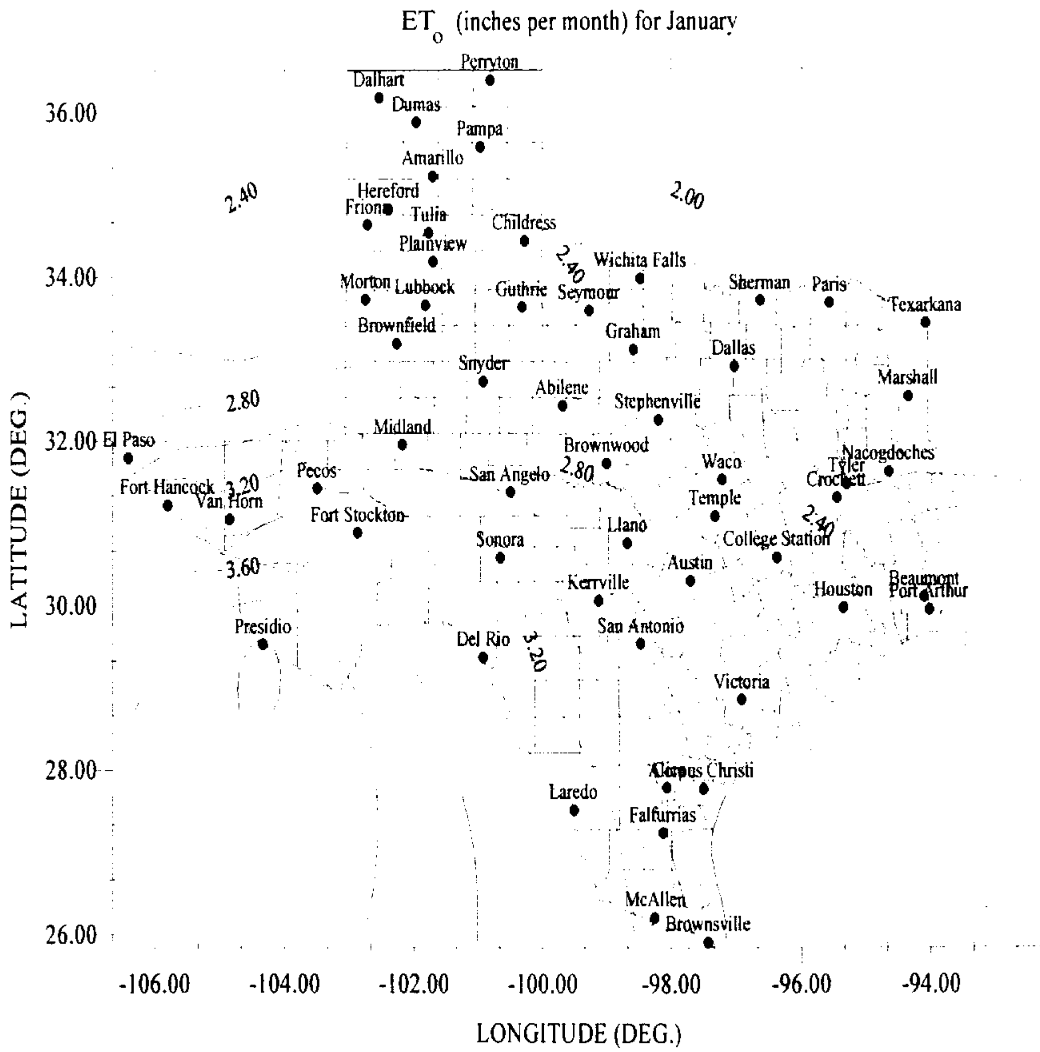


Figure 10.-Grass Reference Crop Evapotranspiration (ET_o) for January (in./mon).

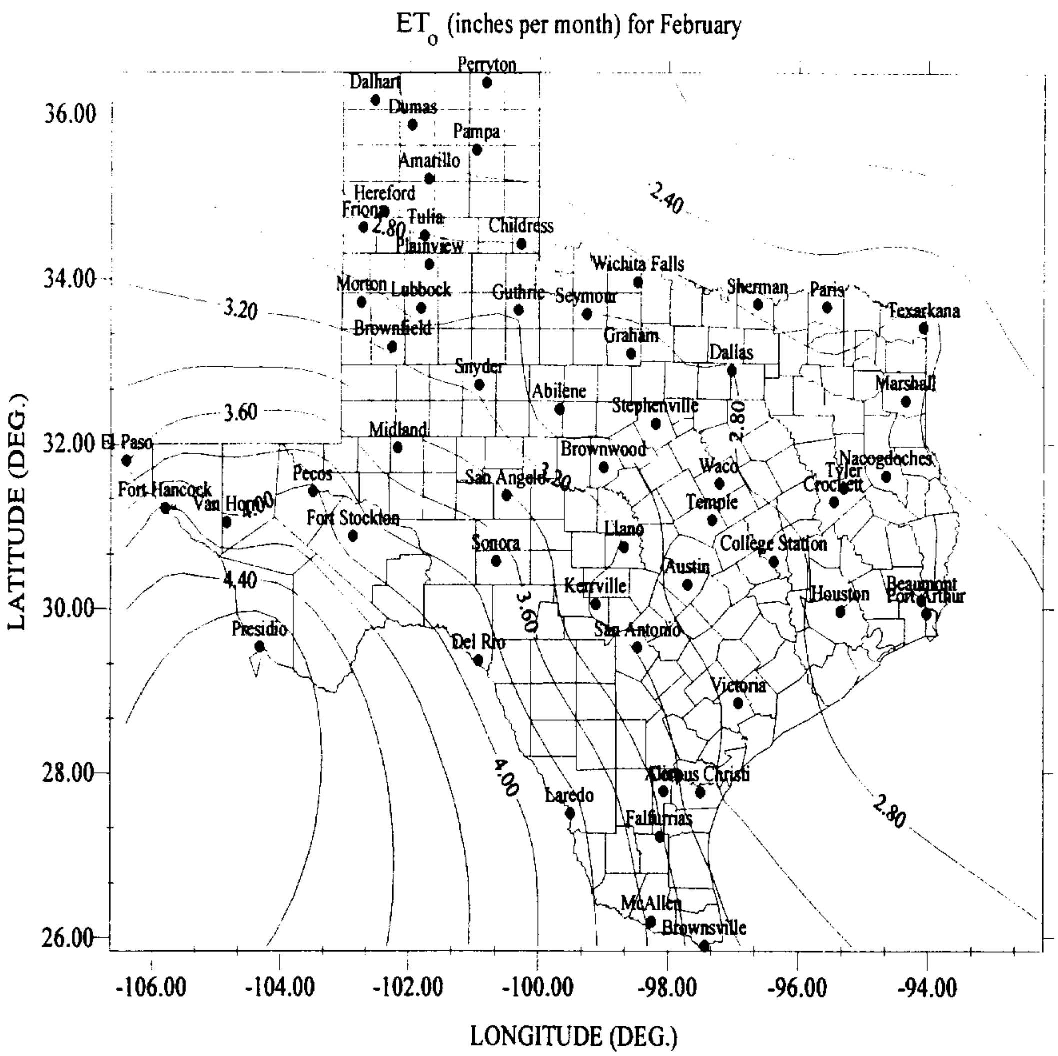


Figure 11.-Grass Reference Crop Evapotranspiration (ET_o) for February (in./mon).

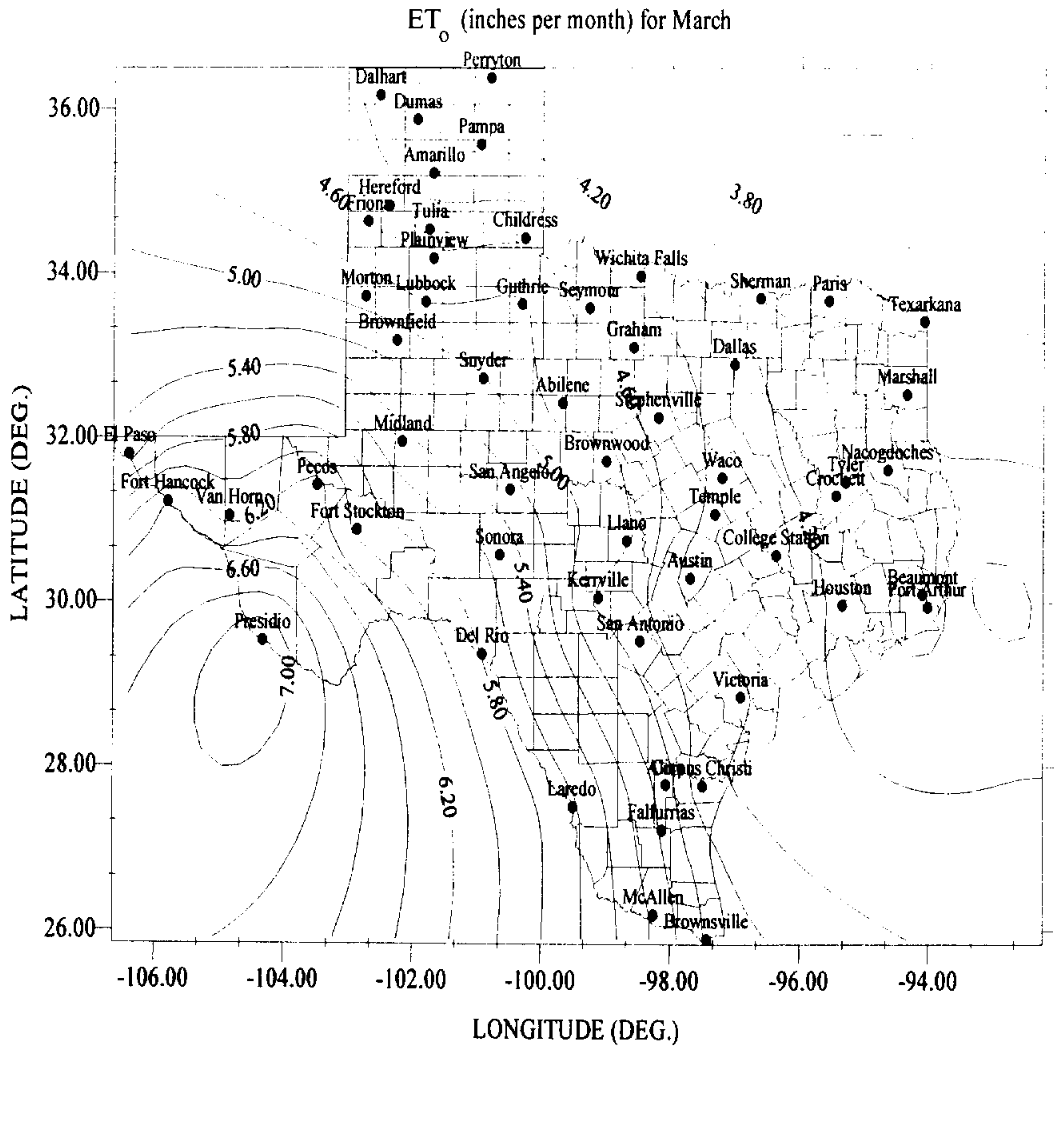


Figure 12.-Grass Reference Crop Evapotranspiration (ET_o) for March (in./mon).

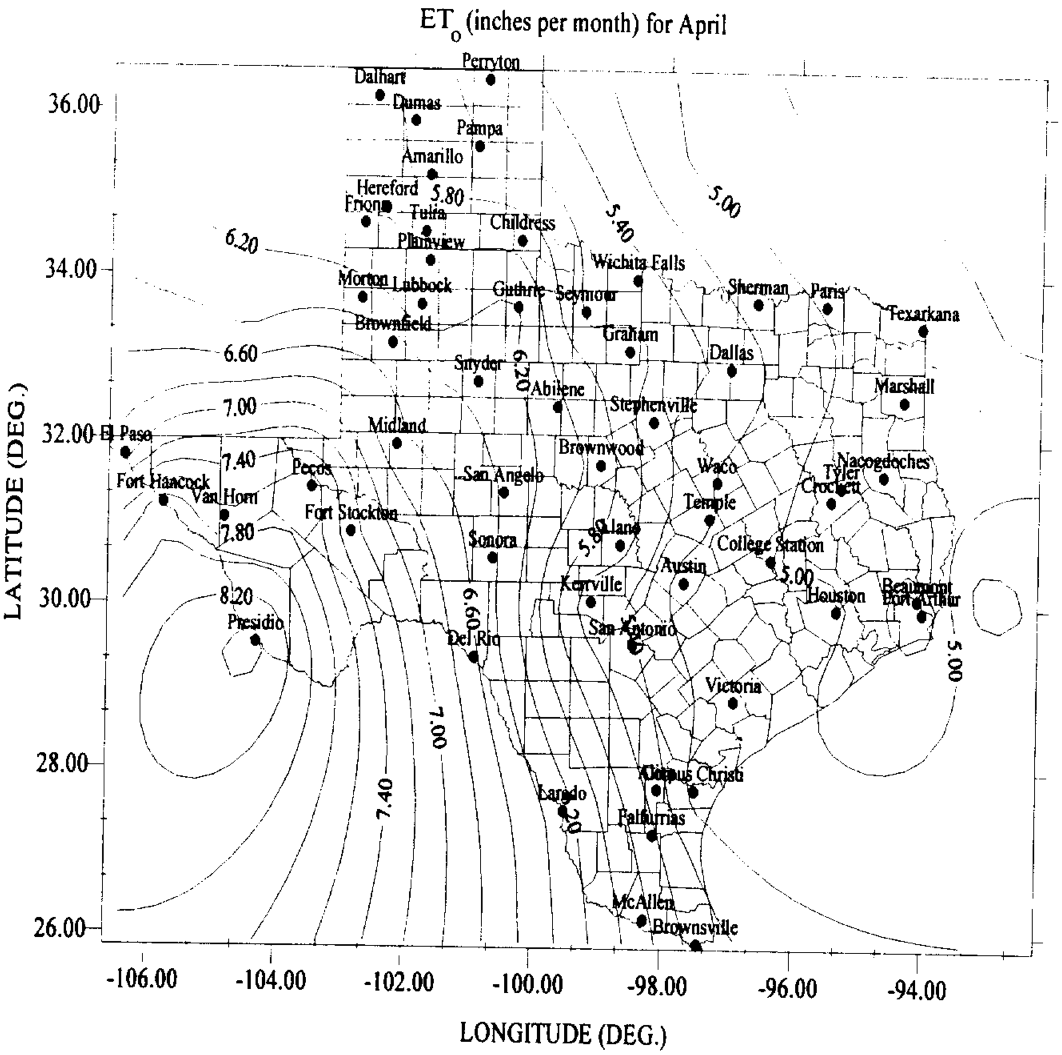


Figure 13.-Grass Reference Crop Evapotranspiration (ET_o) for April (in./mon).

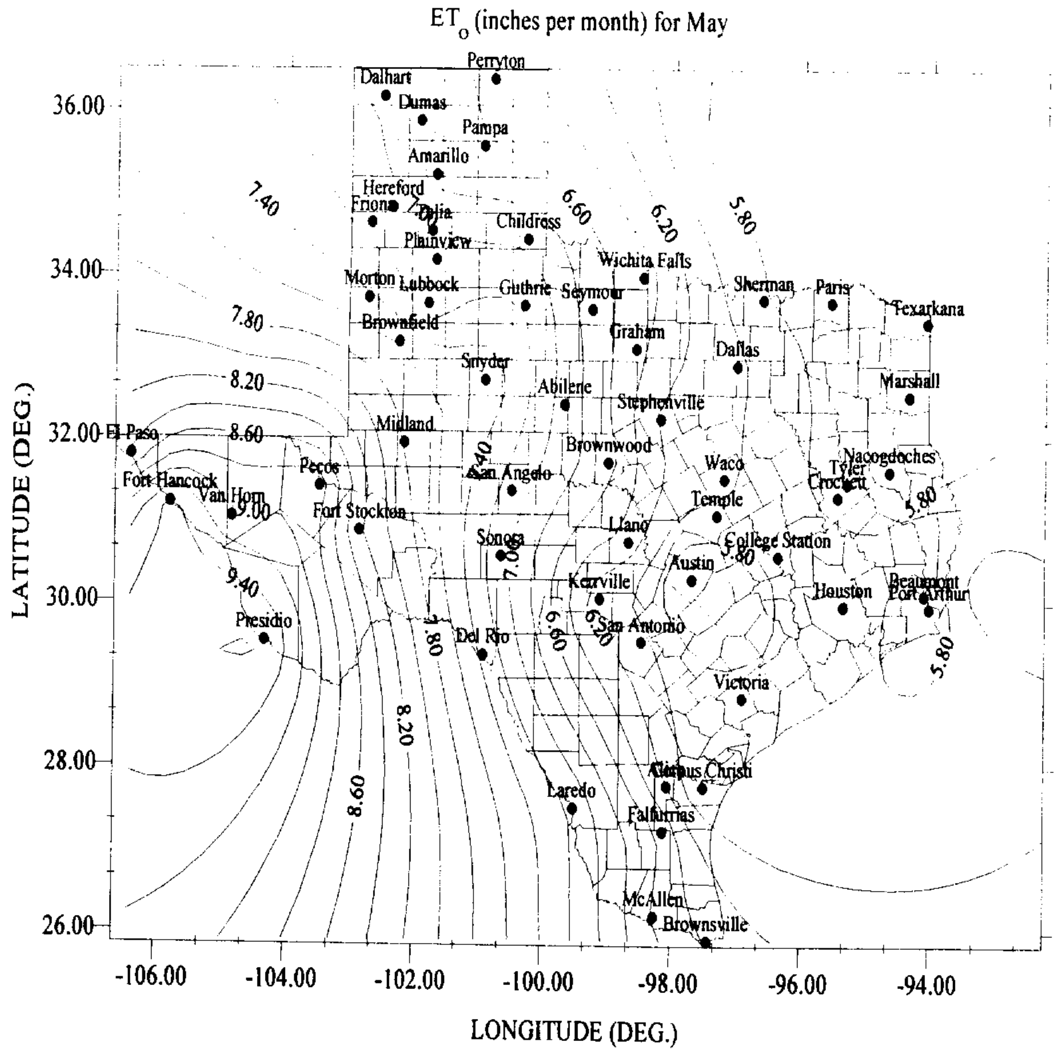


Figure 14.-Grass Reference Crop Evapotranspiration (ET_o) for May (in./mon).

ET$_o$ (inches per month) for June

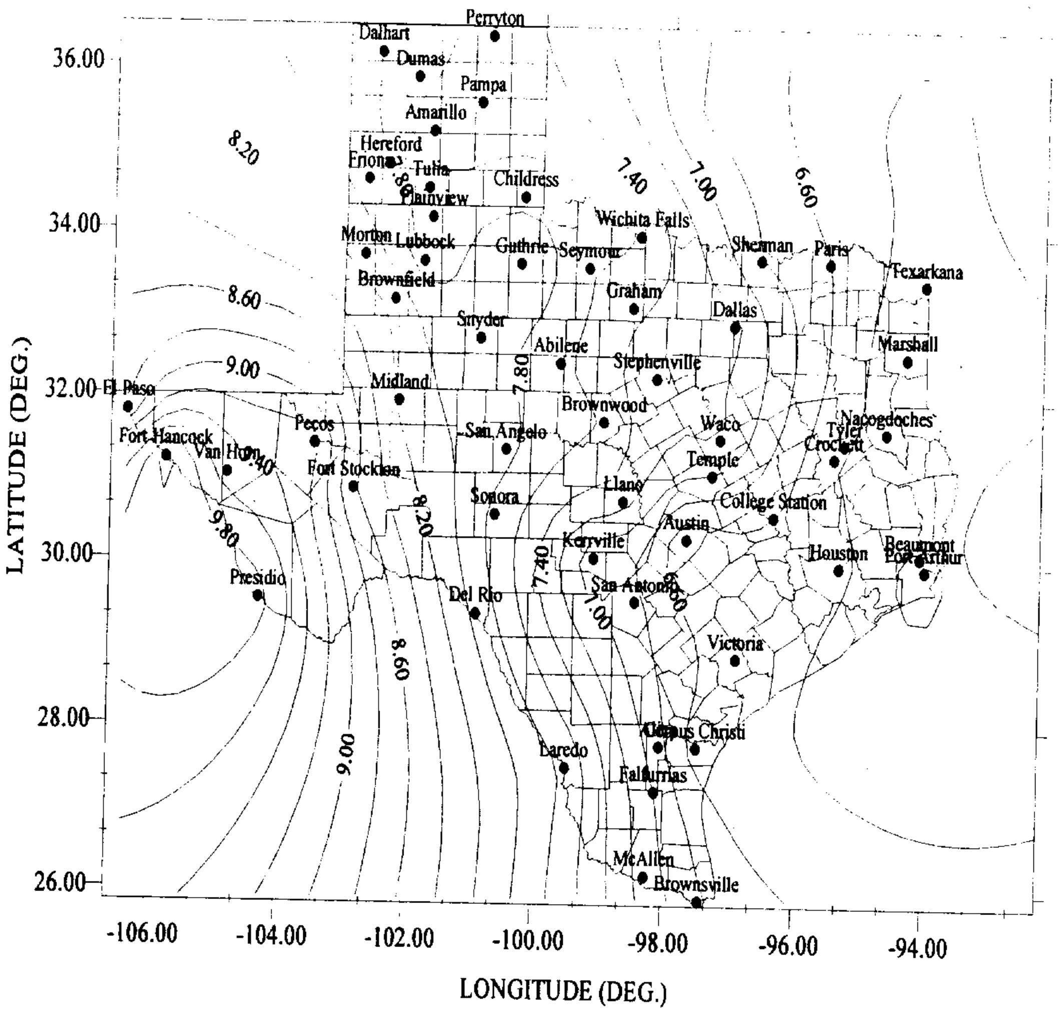


Figure 15.-Grass Reference Crop Evapotranspiration (ET$_o$) for June (in./mon).

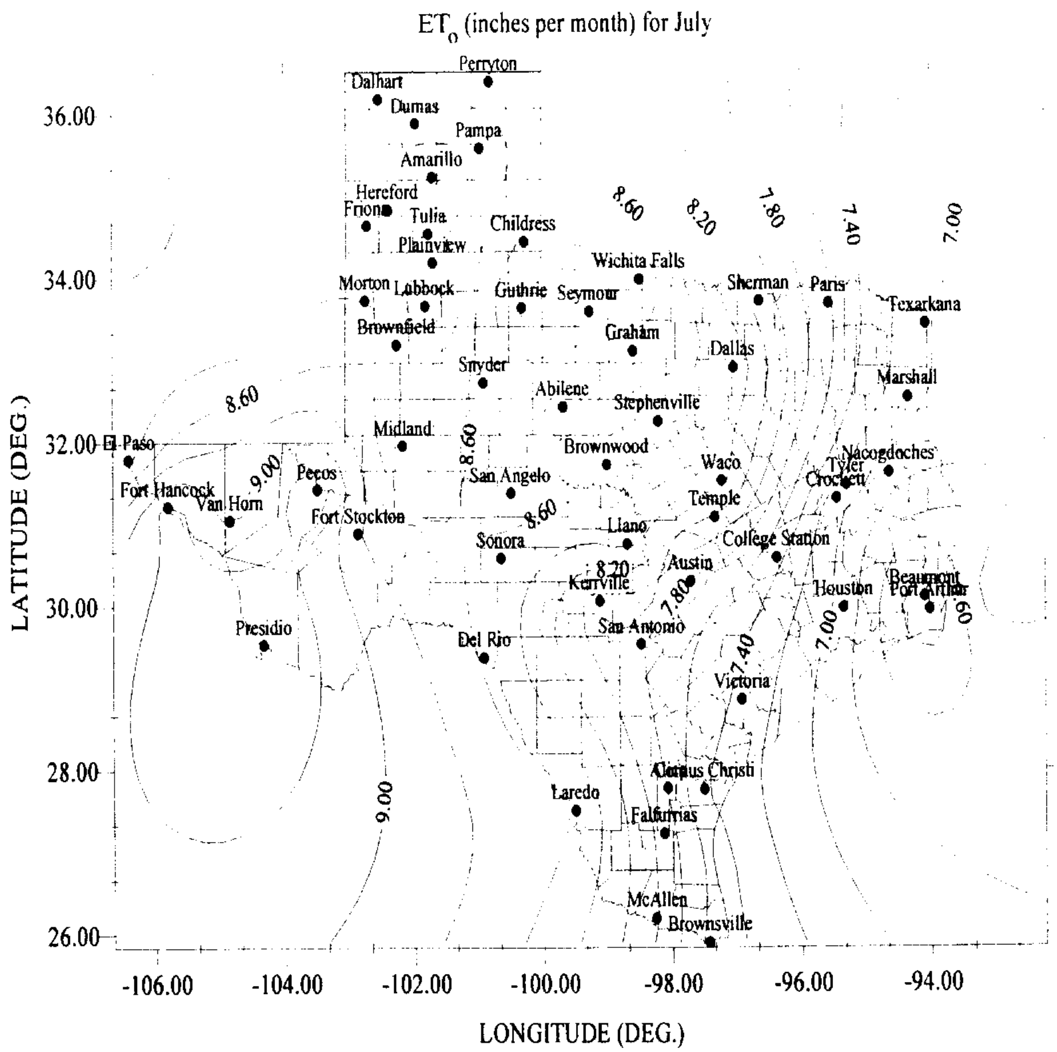


Figure 16.-Grass Reference Crop Evapotranspiration (ET_o) for July (in./mon).

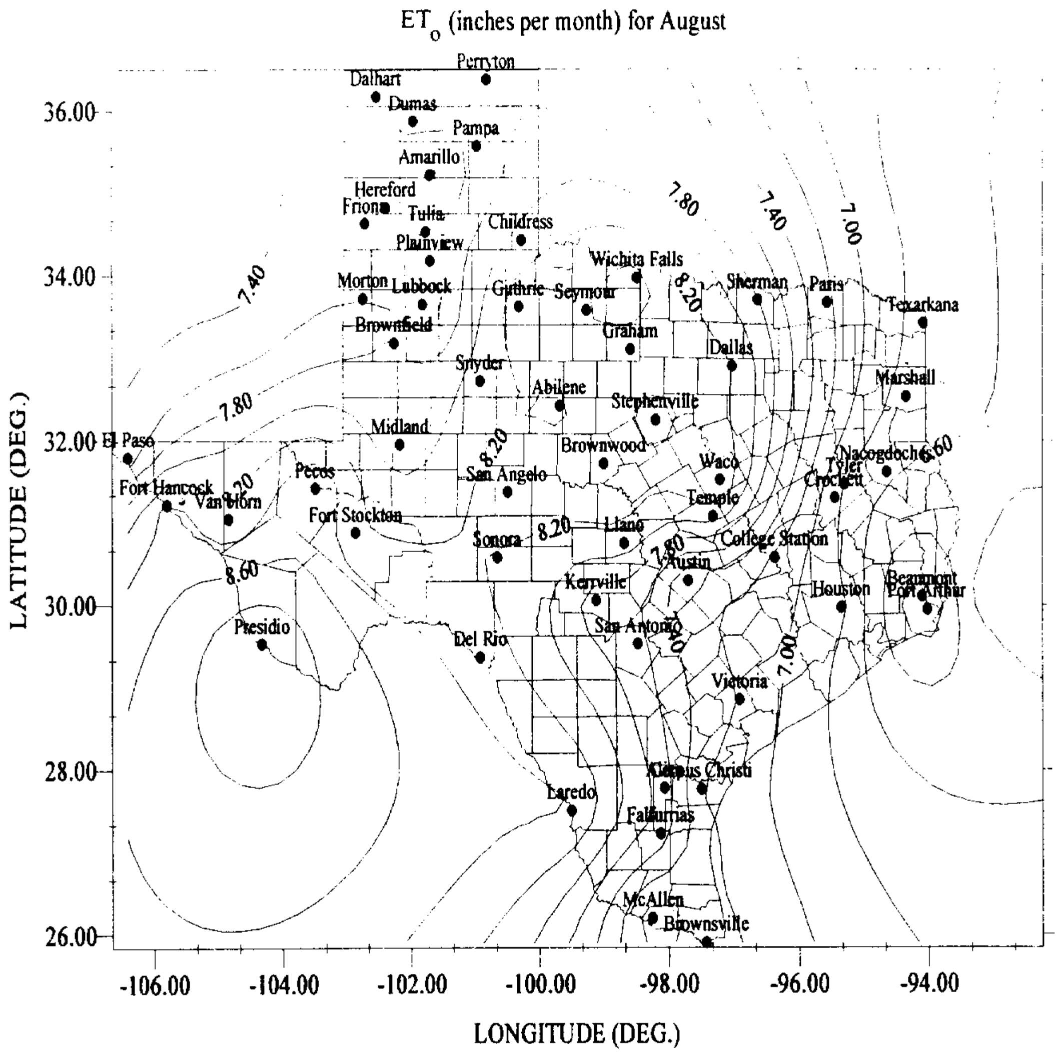


Figure 17.-Grass Reference Crop Evapotranspiration (ET_o) for August (in./mon).

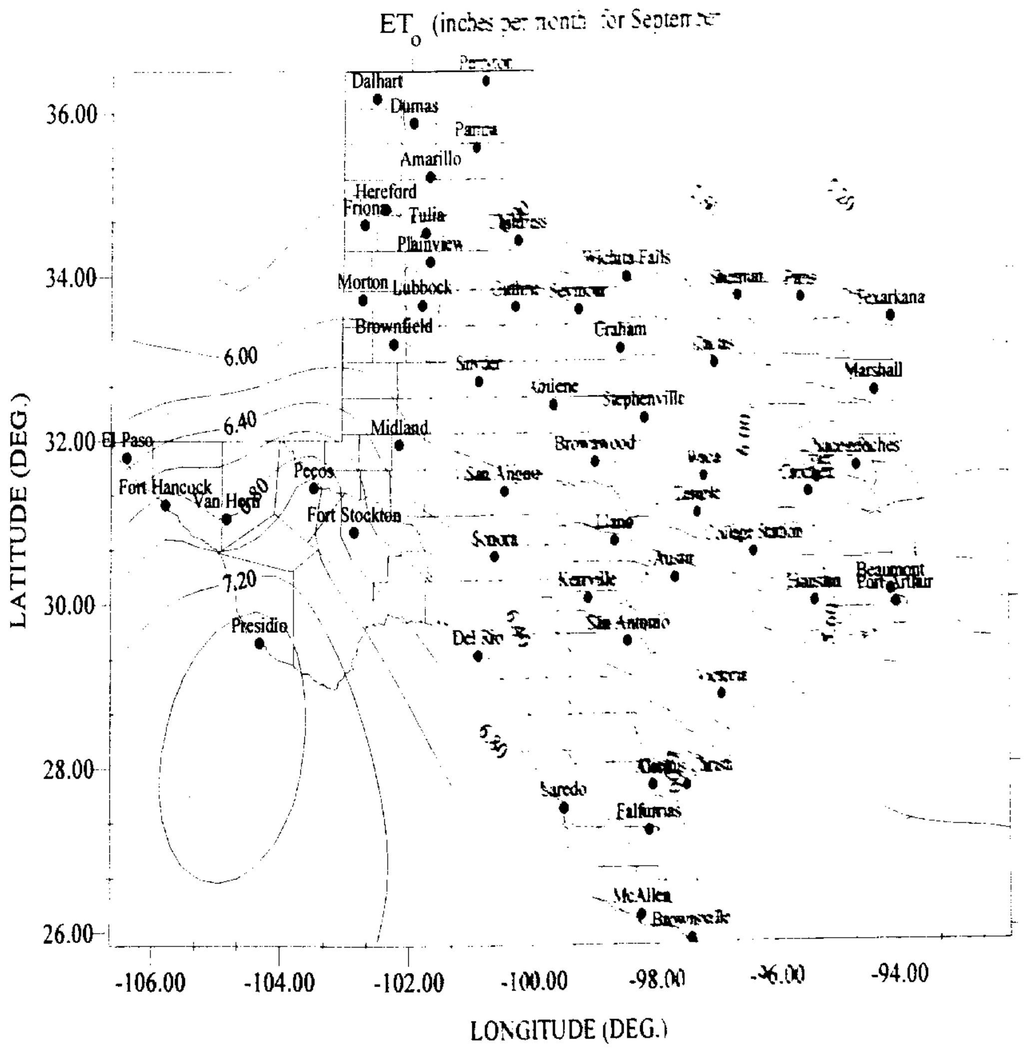


Figure 18.-Grass Reference Crop Evapotranspiration (ET_o) for September (in./mon).

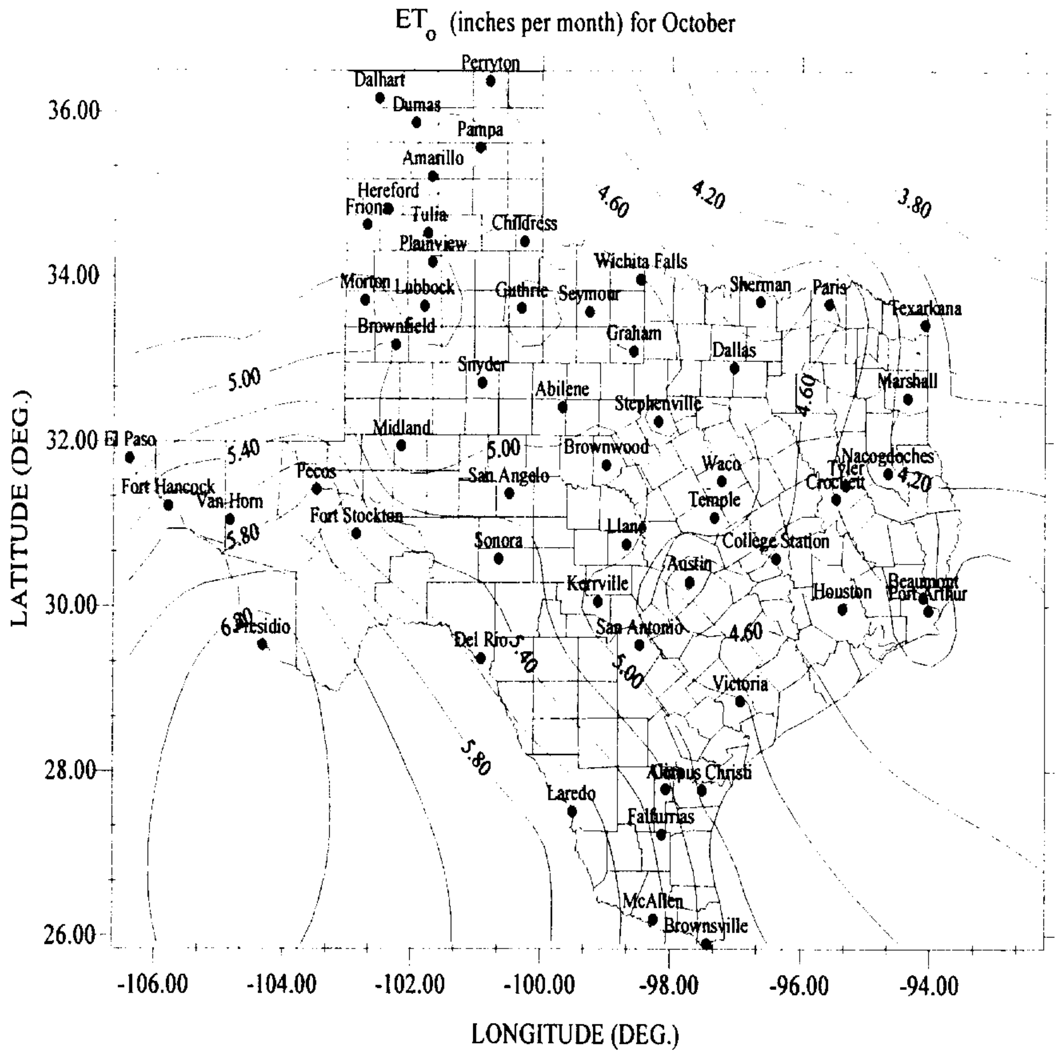


Figure 19.-Grass Reference Crop Evapotranspiration (ET_o) for October (in./mon).

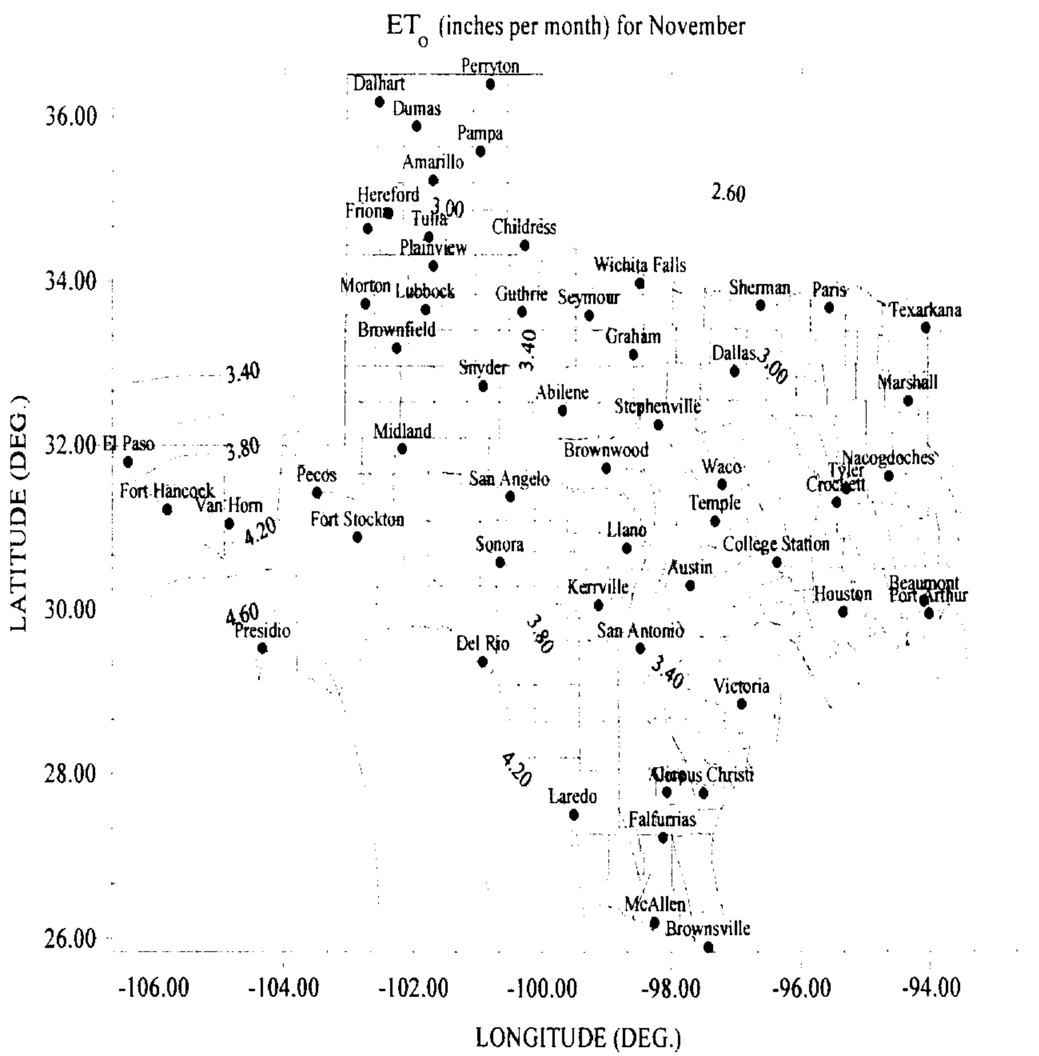


Figure 20.-Grass Reference Crop Evapotranspiration (ET_o) for November (in./mon).

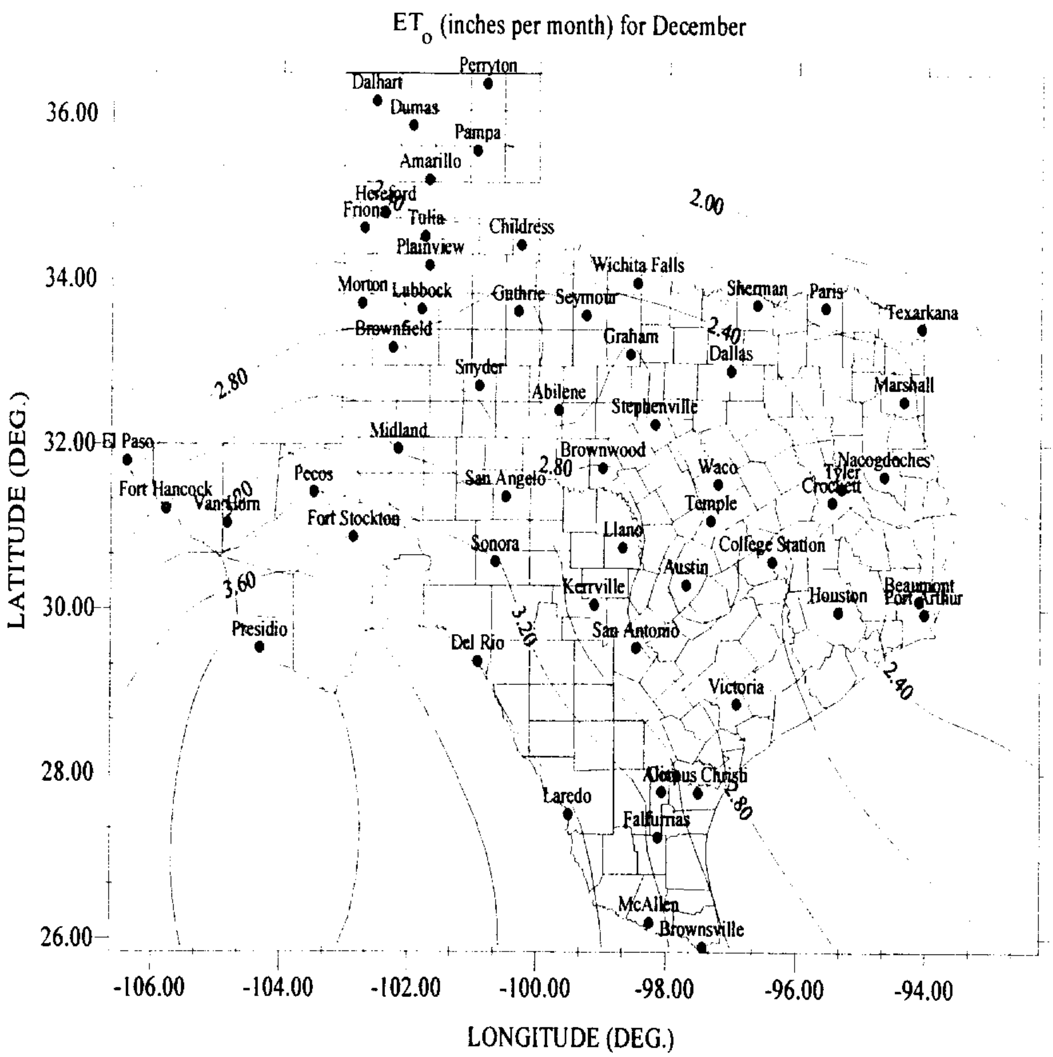


Figure 21.-Grass Reference Crop Evapotranspiration (ET_o) for December (in./mon).

Table 5.-Grass Reference Crop Evapotranspiration (ET_o) (in./mon).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly Total
Abilene	2.61	2.83	4.68	6.05	6.91	7.62	8.50	8.14	6.22	4.86	3.31	2.51	64.2
Alice	2.99	3.36	4.92	5.52	6.20	6.88	7.80	7.71	6.23	5.28	3.83	3.17	63.9
Amarillo	2.36	2.65	4.27	5.70	6.70	7.38	8.08	7.29	5.61	4.47	2.88	2.28	59.7
Austin	2.70	2.88	4.31	5.10	5.51	6.42	7.76	7.19	5.87	4.35	2.99	2.48	57.6
Beaumont	2.36	2.72	3.93	4.71	5.76	6.18	6.27	6.02	5.16	4.40	3.16	2.41	53.1
Brownfield	2.73	3.18	5.11	6.50	7.59	8.14	8.58	7.82	6.11	5.03	3.49	2.88	67.1
Brownsville	2.95	3.30	4.78	5.52	6.38	6.83	7.55	7.32	6.01	5.14	3.74	3.07	62.6
Brownwood	2.76	3.14	4.88	5.94	6.68	7.61	8.75	8.40	6.33	5.17	3.47	2.83	66.0
Childress	2.47	2.80	4.58	5.94	6.96	7.74	8.83	8.06	6.08	4.89	3.10	2.44	63.9
College Station	2.52	2.89	4.30	5.00	5.83	6.60	7.46	7.15	5.66	4.58	3.21	2.66	57.9
Corpus Christi	2.72	3.02	4.44	5.10	5.77	6.49	7.41	7.19	5.84	4.94	3.50	2.86	59.3
Crockett	2.32	2.71	4.12	4.93	5.76	6.40	7.06	6.85	5.54	4.41	3.07	2.47	55.6
Dalhart	2.37	2.69	4.37	5.86	6.96	7.80	8.42	7.56	5.75	4.64	2.98	2.31	61.7
Del Rio	3.38	3.90	5.74	6.57	7.30	7.88	8.55	8.28	6.60	5.56	4.04	3.38	71.2
Dumas	2.26	2.58	4.23	5.77	6.91	7.71	8.59	7.70	5.83	4.65	2.91	2.24	61.4
El Paso	2.83	3.54	5.48	6.89	8.37	8.78	8.30	7.46	6.30	4.97	3.58	2.65	69.2
Falfurrias	3.02	3.43	4.98	5.65	6.59	7.01	7.93	7.72	6.28	5.35	3.85	3.15	64.9
Fort Davis	3.40	3.93	5.86	7.04	8.11	8.45	8.11	7.58	6.36	5.35	4.01	3.33	71.5
Fort Hancock	3.44	4.29	6.43	7.97	9.48	10.1	9.30	8.47	6.94	5.77	4.25	3.30	79.8
Fort Stockton	3.34	3.88	5.93	7.25	8.20	8.60	8.79	8.22	6.65	5.53	4.09	3.37	73.8
Fort Worth	2.50	2.82	4.31	5.38	6.05	7.28	8.56	8.23	6.23	4.72	3.11	2.56	61.8
Friona	2.50	2.81	4.58	6.01	7.12	7.92	8.31	7.51	5.84	4.72	3.15	2.50	63.0
Graham	2.55	2.91	4.58	5.71	6.46	7.45	8.74	8.35	6.34	5.03	3.34	2.64	64.1
Guthrie	2.71	3.00	4.84	6.25	7.20	8.04	9.07	8.34	6.32	5.10	3.45	2.68	67.0
Hereford	2.43	2.76	4.49	5.99	7.08	7.84	8.34	7.50	5.81	4.76	3.11	2.44	62.5
Houston	2.55	2.72	4.17	5.06	5.94	6.47	6.94	6.88	5.76	4.51	3.12	2.46	56.6
Kerrville	2.81	3.13	4.74	5.44	6.04	6.84	7.86	7.68	5.90	4.88	3.47	2.86	61.6
Laredo	3.35	3.87	5.65	6.29	7.18	7.79	8.61	8.43	6.82	5.72	4.18	3.43	71.3
Llano	2.93	3.22	4.85	5.71	6.34	7.32	8.48	8.14	6.20	5.09	3.57	2.95	64.8
Lubbock	2.49	2.92	4.78	6.00	7.05	7.65	7.94	7.33	5.63	4.55	3.15	2.50	62.0

Table 5.-Grass Reference Crop Evapotranspiration (ET_o) (in./mon). (continued)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly Total
Marshall	2.19	2.66	3.99	4.90	5.69	6.25	7.09	6.72	5.32	4.14	2.88	2.28	54.1
McAllen	3.13	3.58	5.17	5.86	6.57	7.12	8.03	7.06	6.41	5.49	4.00	3.28	65.7
Midland	2.92	3.45	5.44	6.65	7.77	8.14	8.39	7.87	6.25	4.83	3.50	2.98	68.2
Morton	2.68	3.08	4.92	6.30	7.42	8.12	8.39	7.58	5.92	4.86	3.40	2.71	65.4
Nacogdoches	2.19	2.64	4.07	4.89	5.78	6.34	6.86	6.64	5.45	4.21	2.97	2.35	54.4
Pampa	2.25	2.52	4.17	5.61	6.61	7.48	8.51	7.67	5.83	4.58	2.86	2.22	60.3
Paris	2.09	2.50	3.91	4.99	5.71	6.61	7.63	7.24	5.49	4.69	2.77	2.14	55.8
Pecos	3.37	4.05	6.28	7.74	8.92	9.29	9.37	8.63	7.10	5.82	4.21	3.44	78.2
Perryton	2.15	2.48	4.02	5.52	6.52	7.55	8.68	7.79	5.89	4.64	2.83	2.14	60.2
Plainview	2.49	2.86	4.63	6.05	7.11	7.78	8.36	7.68	5.87	4.83	3.16	2.53	63.3
Port Arthur	2.25	2.56	3.84	4.63	5.60	6.05	6.18	6.00	5.12	4.23	2.85	2.24	51.5
Presidio	4.04	4.82	7.19	8.49	9.62	9.90	9.42	9.01	7.58	6.37	4.81	3.96	85.2
San Angelo	2.99	3.43	5.27	6.38	7.11	7.87	8.73	8.32	6.21	5.13	3.61	2.98	68.0
San Antonio	2.79	3.19	4.71	5.42	6.08	6.86	7.82	7.68	6.08	4.89	3.41	2.81	61.8
Seymour	2.40	2.81	4.51	5.51	6.69	7.61	8.88	8.40	6.24	4.96	3.14	2.47	63.6
Sherman	2.19	2.56	3.99	5.10	5.82	6.80	8.12	7.81	5.77	4.44	2.89	2.23	57.7
Snyder	2.70	3.18	5.01	6.35	7.56	7.87	8.67	8.10	6.10	4.91	3.44	2.78	66.7
Sonora	3.26	3.72	5.56	6.44	7.06	7.75	8.53	8.18	6.40	5.34	3.81	3.22	69.3
Stephenville	2.48	2.81	4.50	5.44	6.15	7.16	8.40	8.09	6.22	4.70	3.31	2.58	61.8
Temple	2.51	2.83	4.36	5.24	5.96	7.00	8.18	8.11	6.12	4.97	3.30	2.60	61.2
Texarkana	2.12	2.67	3.97	4.96	5.70	6.31	7.02	6.72	5.28	4.06	2.90	2.16	53.9
Tulia	2.49	2.81	4.54	5.98	7.05	7.73	8.37	7.61	5.84	4.80	3.14	2.46	62.8
Tyler	2.16	2.59	3.98	4.88	5.68	6.42	7.16	6.77	5.41	4.31	2.94	2.35	54.7
Uvalde	4.30	4.03	4.81	4.82	5.41	6.01	7.16	7.47	6.68	6.20	5.24	4.76	66.9
Van Horn	3.27	3.99	6.08	7.60	8.99	9.46	8.94	8.20	6.75	5.63	4.04	3.21	76.2
Victoria	2.65	2.97	4.44	5.13	5.86	6.55	7.36	7.20	5.80	4.83	3.38	2.76	58.9
Waco	2.47	2.82	4.35	5.18	6.05	7.23	8.50	8.43	6.32	5.03	3.26	2.55	62.2
Wichita Falls	2.33	2.67	4.35	5.48	6.50	7.63	8.96	8.47	6.22	4.83	3.03	2.34	62.8

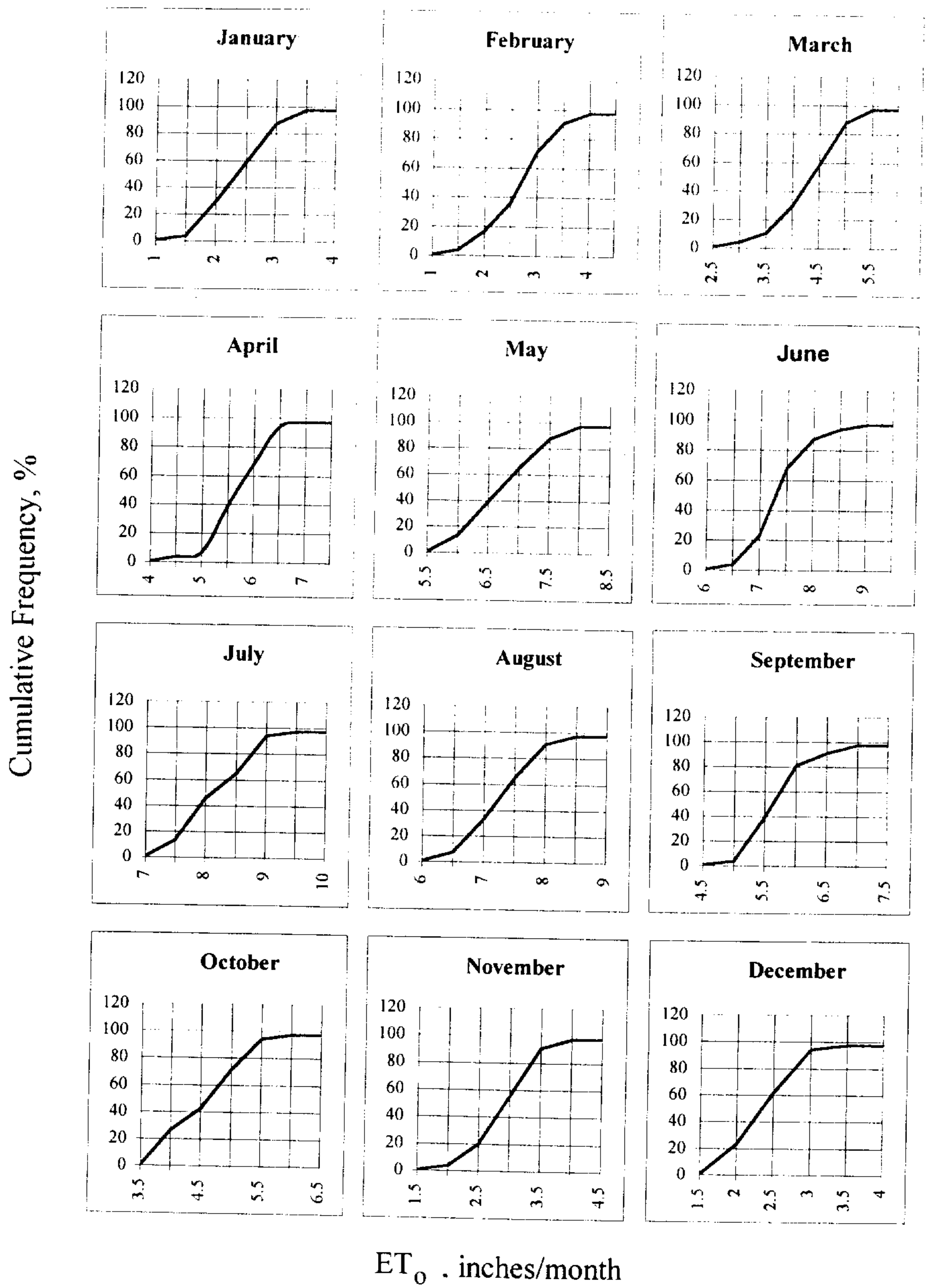


Figure 22.-Cumulative Frequency of Grass Reference Crop Evapotranspiration (ET_0) for Amarillo, TX.

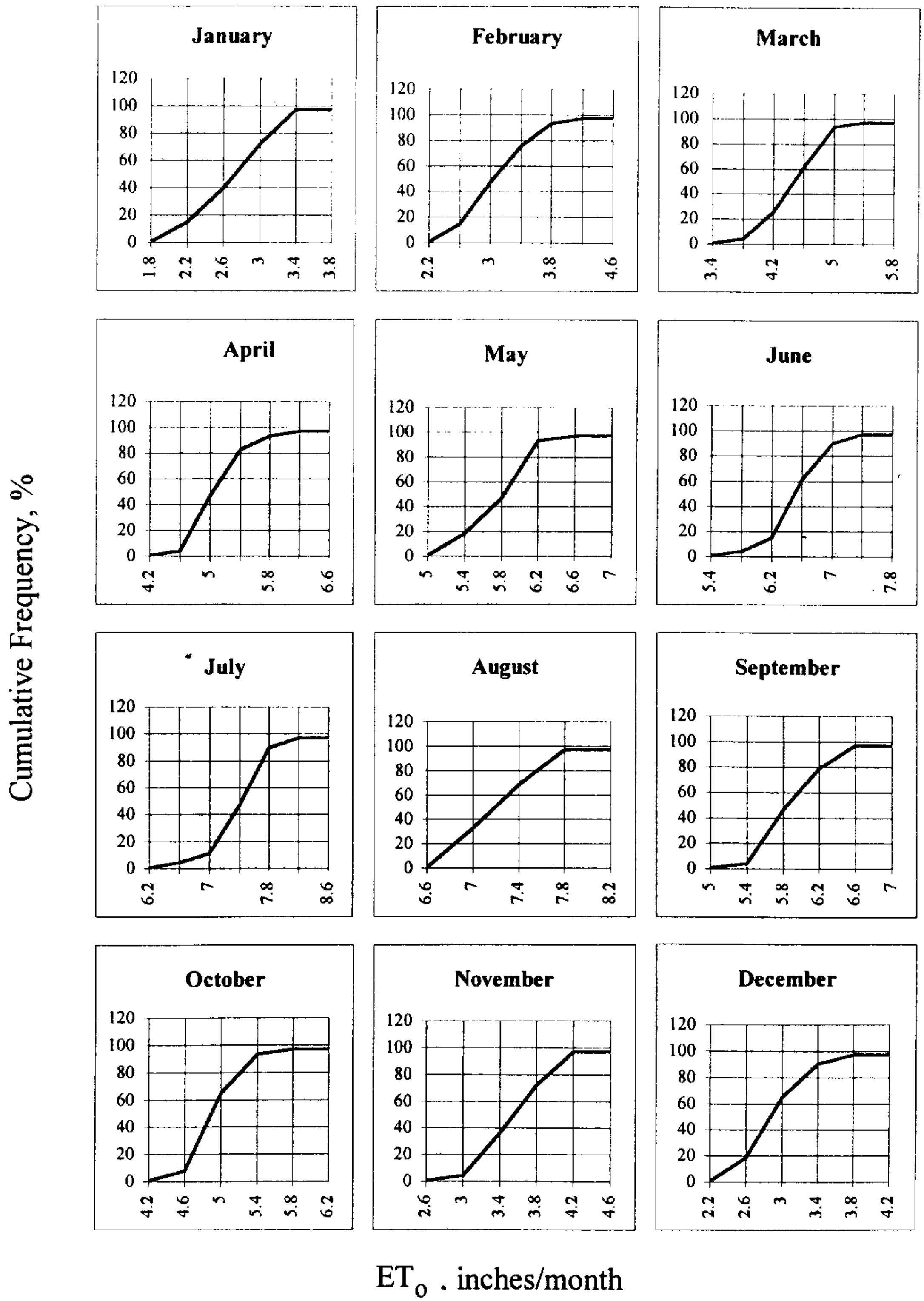


Figure 23.-Cumulative Frequency of Grass Reference Crop Evapotranspiration (ET_o) for Corpus Christi, TX.

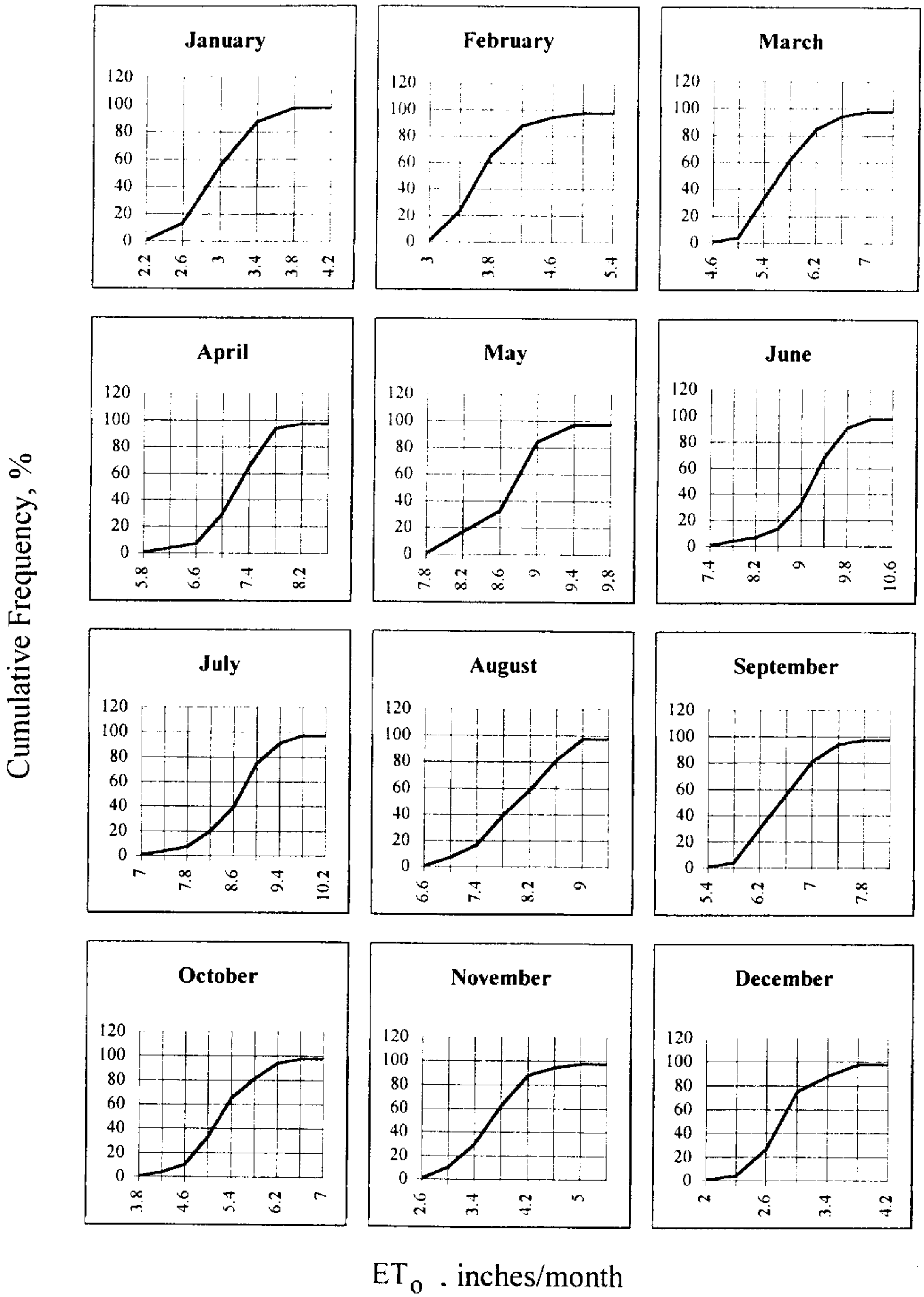


Figure 24.-Cumulative Frequency of Grass Reference Crop Evapotranspiration (ET_o) for El Paso, TX.

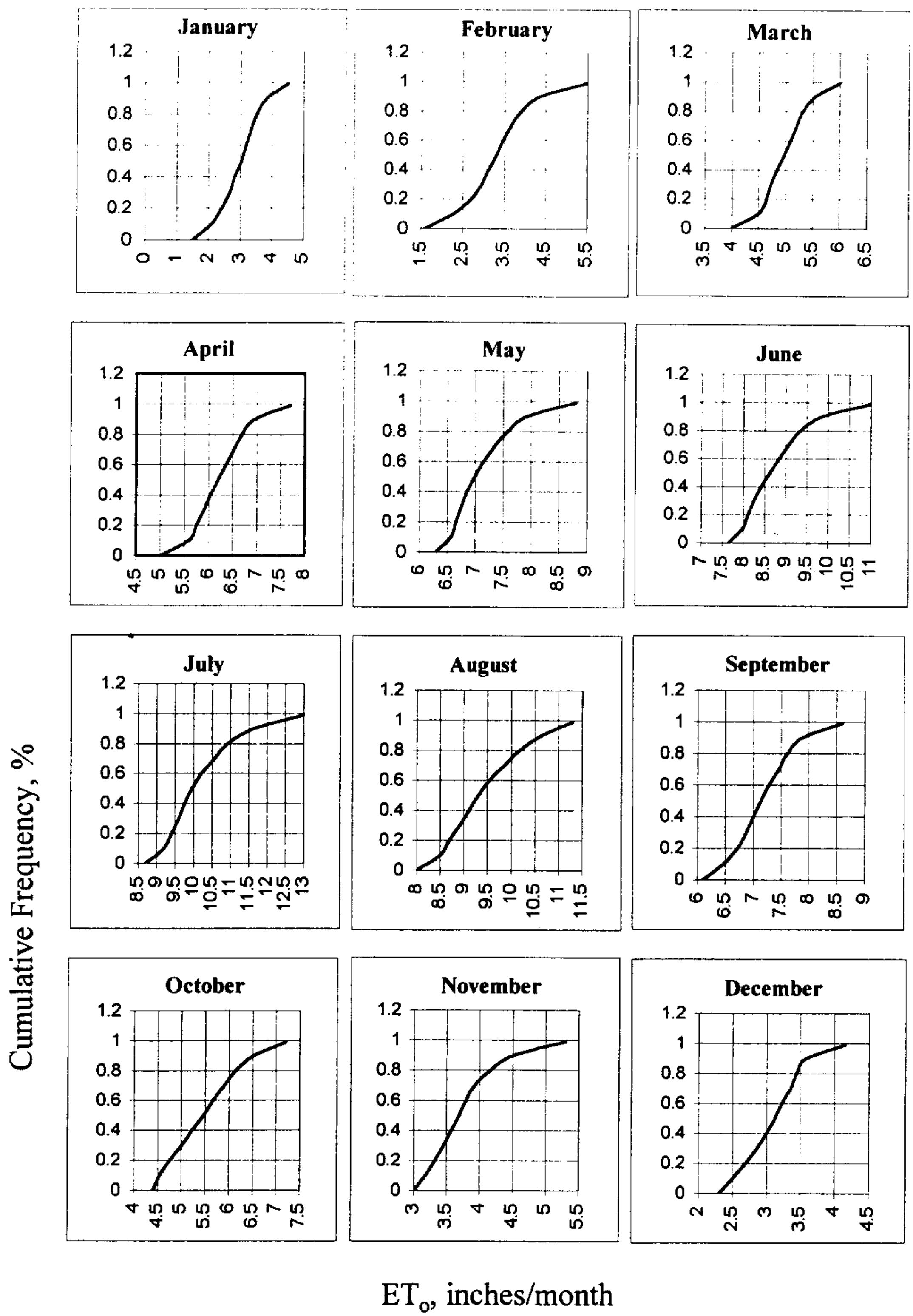


Figure 25.-Cumulative Frequency of Grass Reference Crop Evapotranspiration (ET_o) for Fort Worth, TX.

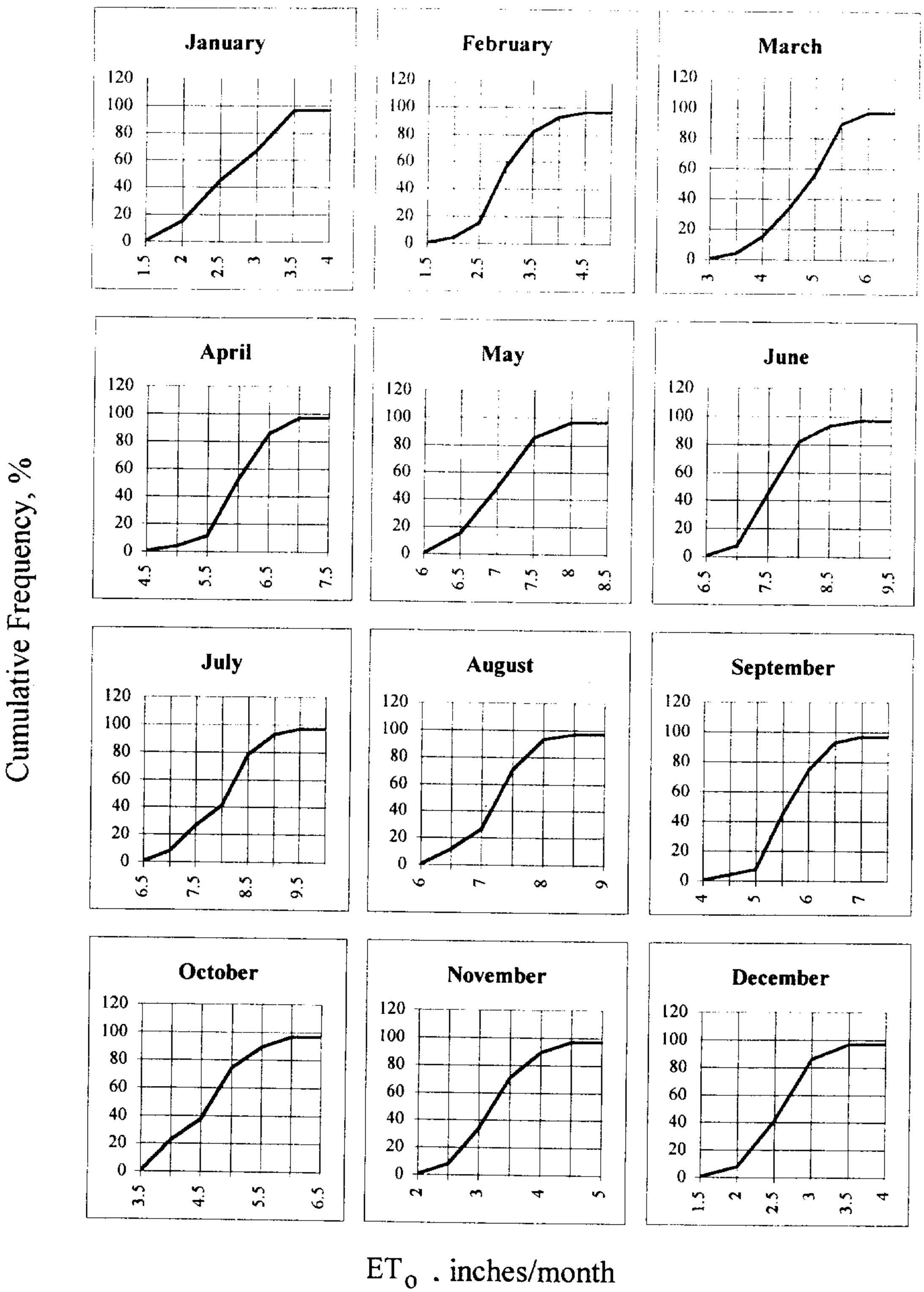


Figure 26.-Cumulative Frequency of Grass Reference Crop Evapotranspiration (ET_o) for Lubbock, TX.

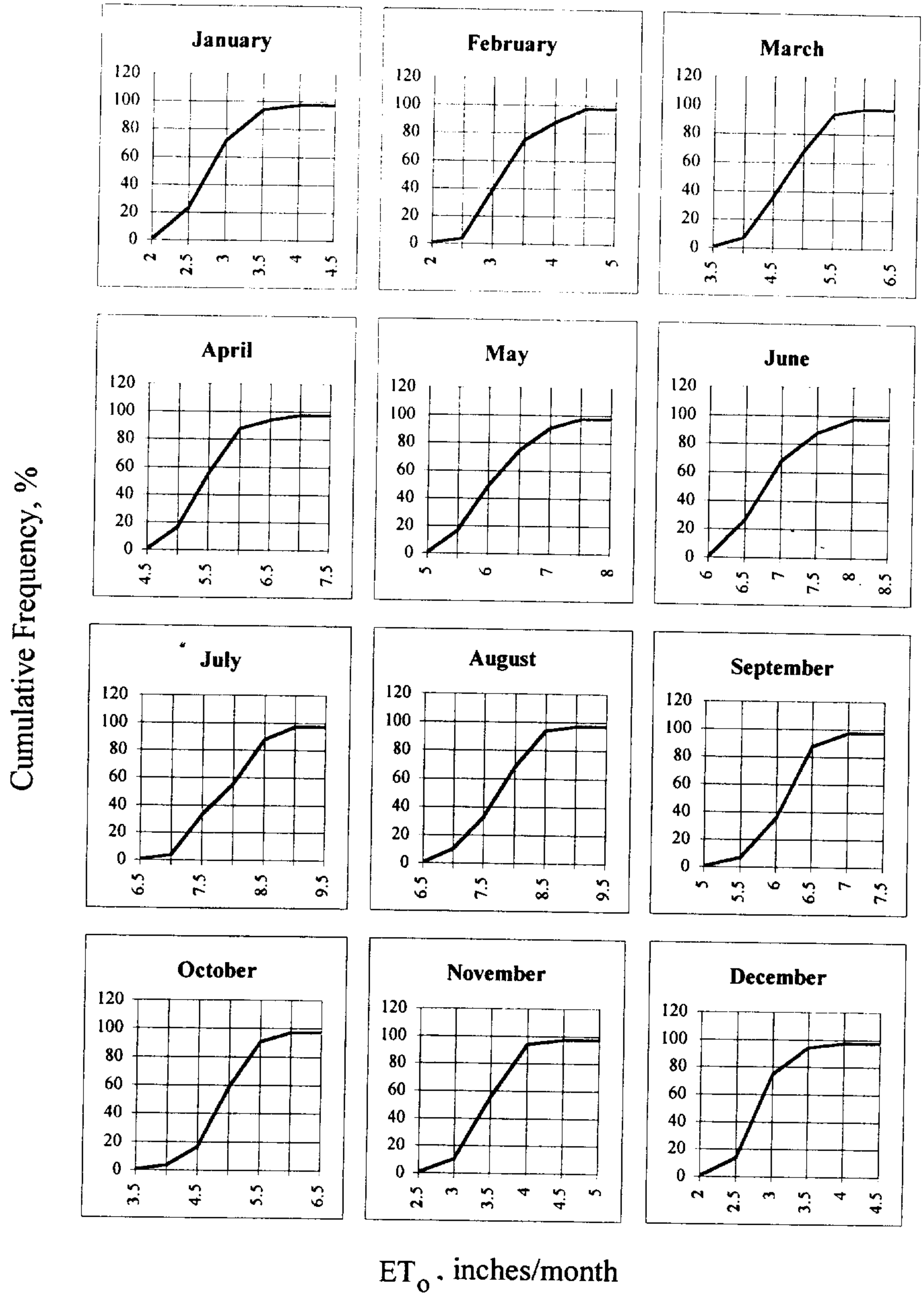


Figure 27.-Cumulative Frequency of Grass Reference Crop Evapotranspiration (ET_o) for San Antonio, TX.

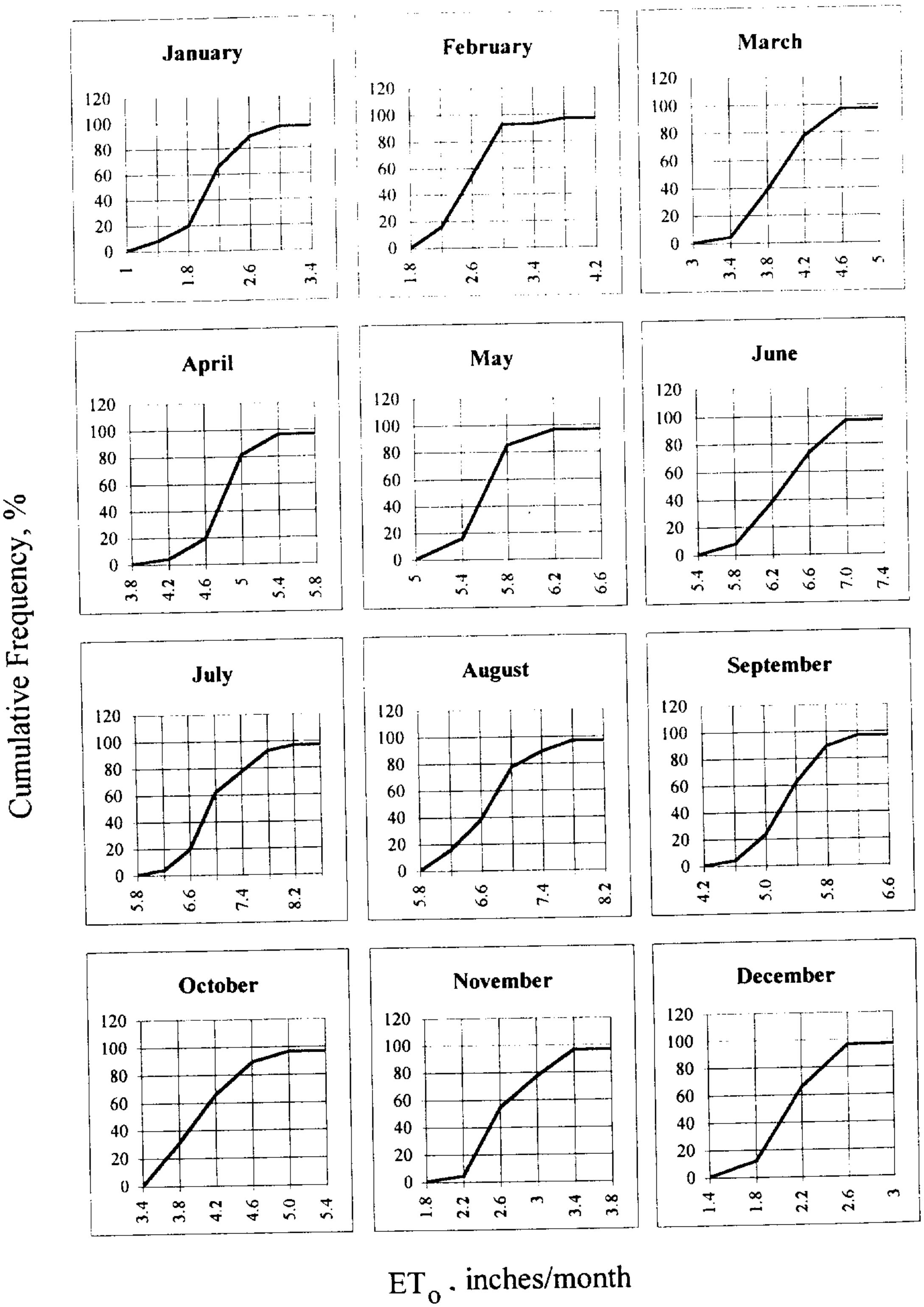


Figure 28.-Cumulative Frequency of Grass Reference Crop Evapotranspiration (ET_o) for Shreveport, LA.

Table 6. - Basal Crop Coefficient Parameters for Field and Vegetable Crops for a Grass Reference Crop (adapted from SCS, 1993).

Crop	Climate	----Crop Coefficients----				Fraction of Season for Start of Stages			Days from Planting Until Maturity
		Moderate Wind		*Strong Wind*					
		k_{cp}	k_{cm}	k_{cp}	k_{cm}	F_{S1}	F_{S2}	F_{S3}	
Artichoke	Humid	0.95	0.90	0.95	0.90	0.10	0.20	0.90	310 - 360
	Arid	1.00	0.95	1.05	1.00				
Barley	Humid	1.05	0.25	1.10	0.25	0.13	0.33	0.75	120 - 150
	Arid	1.15	0.20	1.20	0.20				
Beans, green	Humid	0.95	0.85	0.95	0.85	0.22	0.56	0.89	70 - 90
	Arid	1.00	0.90	1.05	0.90				
Beans, dry	Humid	1.05	0.30	1.10	0.30	0.16	0.42	0.80	90 - 110
	Arid	1.15	0.25	1.20	0.25				
Beets, table	Humid	1.00	0.90	1.00	0.90	0.25	0.60	0.88	70 - 90
	Arid	1.05	0.95	1.10	1.00				
Carrots	Humid	1.00	0.70	1.05	0.75	0.20	0.50	0.83	100 - 150
	Arid	1.00	0.80	1.15	0.85				
Castorbeans	Humid	1.05	0.50	1.10	0.50	0.14	0.36	0.72	160 - 180
	Arid	1.15	0.50	1.20	0.50				
Celery	Humid	1.00	0.90	1.05	0.95	0.15	0.40	0.89	120 - 210
	Arid	1.10	1.00	1.15	1.05				
Corn, sweet	Humid	1.05	0.95	1.10	1.00	0.22	0.56	0.89	80 - 110
	Arid	1.15	1.05	1.20	1.10				
Corn, grain	Humid	1.05	0.55	1.10	0.55	0.17	0.45	0.78	105 - 150
	Arid	1.15	0.60	1.20	0.60				
Cotton	Humid	1.05	0.65	1.15	0.65	0.15	0.60	0.90	150 - 160
	Arid	1.20	0.65	1.25	0.70				
Crucifers:	Humid	0.95	0.80	1.00	0.85	spring planting			80 - 190
brussels,	Arid	1.05	0.90	1.10	0.95	0.18	0.63	0.89	
cabbage									
broccoli,						autumn planting			
cauliflower						0.15	0.33	0.79	
Cucumber:	Humid	0.90	0.70	0.90	0.70	0.19	0.47	0.85	100 - 130
fresh market	Arid	0.95	0.75	1.00	0.80				

Moderate wind is defined as mean wind run less than or equal to 250 miles per day.
Strong wind is defined as mean wind run greater than 250 miles per day.
Humid is defined a mean minimum relative humidity equal to or greater than 70 percent.
Arid is defined as mean minimum relative humidity equal to or less than 20 percent.

Table 6. - Basal Crop Coefficient Parameters for Field and Vegetable Crops for a Grass Reference Crop (adapted from SCS, 1993)(continued).

Crop	Climate	----Crop Coefficients---- *Moderate Wind* k_{cp}	k_{cm}	*Strong Wind* k_{cp}	k_{cm}	Fraction of Season for Start of Stages F_{S1}	F_{S2}	F_{S3}	Days from Planting Until Maturity
Cucumber: mach. harvest	Humid	0.90	0.85	0.90	0.85	0.19	0.47	0.85	90 - 120
	Arid	0.95	0.95	1.00	1.00				
Eggplant	Humid	0.95	0.80	1.00	0.85	0.22	0.54	0.84	130 - 140
	Arid	1.05	0.85	1.10	0.90				
Flax	Humid	1.00	0.25	1.05	0.25	0.15	0.36	0.75	150 - 220
	Arid	1.10	0.20	1.15	0.20				
Grain, small	Humid	1.05	0.30	1.10	0.30	0.15	0.35	0.75	150 - 165
	Arid	1.15	0.25	1.20	0.25				
Lentil	Humid	1.05	0.30	1.10	0.30	0.15	0.35	0.75	150 - 170
	Arid	1.15	0.25	1.20	0.25				
Lettuce	Humid	0.95	0.90	0.95	0.90	0.26	0.63	0.90	70 - 140
	Arid	1.00	0.90	1.05	1.00				
Melons	Humid	1.10	0.65	1.10	0.65	0.20	0.50	0.85	120 - 160
	Arid	1.15	0.75	1.20	0.75				
Millet	Humid	1.00	0.30	1.05	0.30	0.15	0.36	0.75	105 - 140
	Arid	1.10	0.25	1.15	0.25				
Oats	Humid	1.05	0.25	1.10	0.25	0.13	0.33	0.75	120 - 150
	Arid	1.15	0.20	1.20	0.20				
Onion, dry	Humid	0.95	0.75	0.95	0.75	0.10	0.26	0.75	150 - 210
	Arid	1.05	0.80	1.10	0.85				
Onion, green	Humid	0.95	0.95	0.95	0.95	0.28	0.74	0.90	70 - 100
	Arid	1.00	1.00	1.05	1.05				
Peanuts	Humid	0.95	0.55	1.00	0.55	0.20	0.46	0.80	150 - 180
	Arid	1.05	0.60	1.10	0.60				
Peas	Humid	1.05	0.95	1.10	1.00	0.20	0.47	0.85	90 - 110
	Arid	1.15	1.05	1.20	1.10				
Peppers. fresh	Humid	0.95	0.80	1.00	0.85	0.20	0.50	0.85	120 - 210
	Arid	1.05	0.85	1.10	0.90				

Moderate wind is defined as mean wind run less than or equal to 250 miles per day.
Strong wind is defined as mean wind run greater than 250 miles per day.
Humid is defined a mean minimum relative humidity equal to or greater than 70 percent.
Arid is defined as mean minimum relative humidity equal to or less than 20 percent.

Table 6. - Basal Crop Coefficient Parameters for Field and Vegetable Crops for a Grass Reference Crop (adapted from SCS, 1993)(continued).

Crop	Climate	----Crop Coefficients----				Fraction of Season for Start of Stages			Days from Planting Until Maturity
		Moderate Wind		*Strong Wind*					
		k_{cp}	k_{cm}	k_{cp}	k_{cm}	F_{S1}	F_{S2}	F_{S3}	
Potato	Humid	1.05	0.70	1.10	0.70	0.20	0.45	0.80	100 - 150
	Arid	1.15	0.75	1.20	0.75				
Radishes	Humid	0.80	0.75	0.80	0.75	0.20	0.50	0.87	30 - 45
	Arid	0.85	0.80	0.90	0.85				
Safflower	Humid	1.05	0.25	1.10	0.25	0.17	0.45	0.80	120 - 190
	Arid	1.15	0.20	1.20	0.20				
Sorghum	Humid	1.00	0.50	1.05	0.50	0.16	0.42	0.75	110 - 140
	Arid	1.10	0.55	1.15	0.55				
Soybeans	Humid	1.00	0.45	1.05	0.45	0.15	0.37	0.81	100 - 150
	Arid	1.10	0.45	1.15	0.45				
Spinach	Humid	0.95	0.90	0.95	0.90	0.20	0.50	0.90	60 - 100
	Arid	1.00	0.95	1.05	1.00				
Squash, winter or pumpkin	Humid	0.90	0.70	0.90	0.70	0.20	0.50	0.80	90 - 125
	Arid	0.95	0.75	1.00	0.80				
Squash, zucchini crookneck	Humid	0.90	0.70	0.90	0.70	0.25	0.60	0.85	90 - 125
	Arid	0.95	0.75	1.00	0.80				
Strawberry	Humid	0.70	0.70	0.70	0.70	0.10	0.40	1.00	150 - 180
	Arid	0.80	0.80	0.85	0.85				
Sugarbeet	Humid	1.05	0.90	1.10	0.95	0.20	0.46	0.80	160 - 230
	Arid	1.15	1.00	1.20	1.00				
Sunflower	Humid	1.05	0.40	1.10	0.40	0.17	0.45	0.80	90 - 120
	Arid	1.15	0.35	1.20	0.35				
Tomato	Humid	1.05	0.85	1.10	0.85	0.20	0.50	0.80	120 - 180
	Arid	1.20	0.90	1.25	0.90				
Wheat, winter	Humid	1.05	0.25	1.10	0.25	0.13	0.33	0.75	220 - 265
	Arid	1.15	0.20	1.20	0.20				
Wheat, spring	Humid	1.05	0.55	1.10	0.55	0.13	0.53	0.75	100 - 140
	Arid	1.15	0.50	1.20	0.50				

Moderate wind is defined as mean wind run less than or equal to 250 miles per day.
Strong wind is defined as mean wind run greater than 250 miles per day.
Humid is defined a mean minimum relative humidity equal to or greater than 70 percent.
Arid is defined as mean minimum relative humidity equal to or less than 20 percent.

Table 7.-Basal Crop Coefficients for Citrus Grown in Predominantly Dry Areas with Moderate Wind Using a Grass Reference Crop (adapted from National Engineering Handbook 1993).

Ground cover	Weed control	Jan	Feb	Mar	Apr	May	Jun
Large, mature trees providing 70% tree ground cover	Clean cultivated	0.75	0.75	0.70	0.70	0.70	0.65
	No weed control	0.90	0.90	0.85	0.85	0.85	0.85
Trees providing about 50% tree ground cover	Clean cultivated	0.65	0.65	0.60	0.60	0.60	0.55
	No weed control	0.90	0.90	0.85	0.85	0.85	0.85
Trees providing about 20% tree ground cover	Clean cultivated	0.55	0.55	0.50	0.50	0.50	0.45
	No weed control	1.00	1.00	0.95	0.95	0.95	0.95

Ground cover	Weed control	Jul	Aug	Sep	Oct	Nov	Dec
Large, mature trees providing 70% tree ground cover	Clean cultivated	0.65	0.65	0.65	0.70	0.70	0.70
	No weed control	0.85	0.85	0.85	0.85	0.85	0.85
Trees providing about 50% tree ground cover	Clean cultivated	0.55	0.55	0.55	0.55	0.60	0.60
	No weed control	0.85	0.85	0.85	0.85	0.85	0.85
Trees providing about 20% tree ground cover	Clean cultivated	0.45	0.45	0.45	0.45	0.50	0.50
	No weed control	0.95	0.95	0.95	0.95	0.95	0.95

Table 8.- Basal Crop Coefficient for Full Grown Deciduous Fruit and Nut Trees Using a Grass Reference Crop (from National Engineering Handbook 1993).

	---------------------------With ground cover crop(1)---------------------------								
	Mar	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
	Cold winter with killing frost: Ground cover starting in April								
Apple, cherry									
Humid, moderate wind	----	0.50	0.75	1.00	1.10	1.10	1.10	0.85	----
Humid, strong wind	----	0.50	0.75	1.10	1.20	1.20	1.15	0.90	----
Arid, moderate wind	----	0.45	0.85	1.15	1.25	1.25	1.20	0.95	----
Arid, strong wind	----	0.45	0.85	1.20	1.35	1.35	1.25	1.00	----
Peach apricot, pear, plum									
Humid, moderate wind	----	0.50	0.70	0.90	1.00	1.00	0.95	0.75	----
Humid, strong wind	----	0.50	0.70	1.00	1.05	1.10	1.00	0.80	----
Arid, moderate wind	----	0.45	0.80	1.05	1.15	1.15	1.10	0.85	----
Arid, strong wind	----	0.45	0.80	1.10	1.20	1.20	1.15	0.90	----
	Cold winter with light frost: No dormancy in grass cover crops								
Apple, cherry, walnut (2)									
Humid, moderate wind	0.80	0.90	1.00	1.10	1.10	1.10	1.05	0.85	0.80
Humid, strong wind	0.80	0.95	1.10	1.15	1.20	1.20	1.15	0.90	0.80
Arid, moderate wind	0.85	1.00	1.15	1.25	1.25	1.25	1.20	0.95	0.85
Arid, strong wind	0.85	1.05	1.20	1.35	1.35	1.35	1.25	1.00	0.85
Peach, apricot, pear, plum, almond, pecan									
Humid, moderate wind	0.80	0.85	0.90	1.00	1.00	1.00	0.95	0.80	0.80
Humid, strong wind	0.80	0.90	0.95	1.00	1.10	1.10	1.00	0.85	0.80
Arid, moderate wind	0.85	0.95	1.05	1.15	1.15	1.15	1.10	0.90	0.85
Arid, strong wind	0.85	1.00	1.10	1.20	1.20	1.20	1.15	0.95	0.85

(1) For young orchards with tree ground cover of 20 and 50 percent, reduce mid-season Kcb values by 10 to 15 percent and 5 to 1(
(2) For walnut, March through May possibly 10 to 20 percent lower values because slower leaf growth.

Table 9.- Basal Crop Coefficient for Full Grown Deciduous Fruit and Nut Trees Using a Grass Reference Crop (from National Engineering Handbook 1993).

	Clean, cultivated, weed free(1)								
	Mar	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**
	Cold winter with killing frost: Ground cover starting in April								
Apple, cherry									
Humid, moderate wind	----	0.45	0.55	0.75	0.85	0.85	0.80	0.60	----
Humid, strong wind	----	0.45	0.55	0.80	0.90	0.90	0.85	0.65	----
Arid, moderate wind	----	0.40	0.60	0.85	1.00	1.00	0.95	0.70	----
Arid, strong wind	----	0.40	0.65	0.90	1.05	1.05	1.00	0.75	----
Peach apricot, pear, plum									
Humid, moderate wind	----	0.45	0.50	0.65	0.75	0.75	0.70	0.55	----
Humid, strong wind	----	0.45	0.55	0.70	0.80	0.80	0.75	0.60	----
Arid, moderate wind	----	0.40	0.55	0.75	0.90	0.90	0.70	0.65	----
Arid, strong wind	----	0.40	0.60	0.80	0.95	0.95	0.90	0.65	----
	Cold winter with light frost: No dormancy in grass cover crops								
Apple, cherry, walnut (2)									
Humid, moderate wind	0.60	0.70	0.80	0.85	0.85	0.80	0.80	0.75	0.65
Humid, strong wind	0.60	0.75	0.85	0.90	0.90	0.85	0.80	0.80	0.70
Arid, moderate wind	0.50	0.75	0.95	1.00	1.00	0.95	0.90	0.85	0.70
Arid, strong wind	0.50	0.80	1.00	1.05	1.05	1.00	0.95	0.90	0.75
Peach, apricot, pear, plum, almond, pecan									
Humid, moderate wind	0.55	0.70	0.75	0.80	0.80	0.70	0.70	0.65	0.55
Humid, strong wind	0.55	0.70	0.75	0.80	0.80	0.80	0.75	0.70	0.60
Arid, moderate wind	0.50	0.70	0.85	0.90	0.90	0.90	0.80	0.75	0.65
Arid, strong wind	0.50	0.75	0.90	0.95	0.95	0.95	0.85	0.80	0.70

(1) For young orchards with tree ground cover of 20 and 50 percent, reduce mid-season Kcb values by 25 to 35 percent and 10 to 15 percent, respectively.

(2) For walnut, March through May possibly 10 to 20 percent lower values because slower leaf growth.

Table 10.-Basal Crop Coefficients for Grapes with Clean Cultivation, Infrequent Irrigation, and Dry Soil Surface Most of the Season Using a Grass Reference Crop (from National Engineering Handbook 1993).

Conditions (1)	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Mature grapes grown in areas of killing frost, initial leaves early May, harvest mid-September, ground cover 40 to 50 percent at mid-season.									
1	----	----	0.50	0.65	0.75	0.80	0.75	0.65	----
2	----	----	0.50	0.70	0.80	0.85	0.80	0.70	----
3	----	----	0.45	0.70	0.85	0.90	0.80	0.70	----
4	----	----	0.50	0.75	0.90	0.95	0.90	0.75	----
Mature grapes grown in areas of only light frost, initial leaves early April, harvest late August to early September, ground cover 30 to 35 percent at mid-season.									
1	----	0.50	0.55	0.60	0.60	0.60	0.60	0.50	0.40
2	----	0.50	0.55	0.65	0.65	0.65	0.65	0.55	0.40
3	----	0.45	0.60	0.70	0.70	0.70	0.70	0.60	0.35
4	----	0.45	0.65	0.75	0.75	0.75	0.75	0.65	0.35
Mature grapes grown in hot dry areas, initial leaves late February to early March, harvest late half of July, ground cover 30 to 35 percent at mid-season. (2)									
3	0.25	0.45	0.60	0.70	0.70	0.65	0.55	0.45	0.35
4	0.25	0.45	0.65	0.75	0.75	0.70	0.55	0.45	0.35

(1) Relative humidity >70 percent and wind run less than or equal to 250 miles per day
2--Relative humidity greater than 70 percent and wind run greater than 250 miles per day
3--Relative humidity less than or equal to 20 percent and wind run less than or equal to 250 miles per day
4--Relative humidity less than or equal to 20 percent and wind run greater than 250 miles per day

(2) The Kcb values for the last two growing conditions must be reduced if ground cover is less than 35 percent.

Table 11.-Basal Crop Coefficients for Paddy Rice Grown in the United United States Mainland (wet summer--South) Using a Grass Grass Reference Crop (adapted from SCS, 1993)

	Planting	**Harvest**	**First & second month**	**Mid-season**	**Last four weeks**
Moderate wind	May	September	1.10	1.10	0.95
Strong wind		-October	1.15	1.15	1.00

Table 12.-Basal Crop Coefficients (Mean) for Alfalfa. (adapted for SCS, 1993)

Wind Run (miles per day)	K_{cb} Humidity 20%	Humidity 70%
Wind 250	0.95	0.85
Wind >250	1.05	1.05

Table 13.-Growing Season for Major Texas Crops.

	Zones								
	1-N	*1-S*	*2-N*	*2-S*	*3*	*4*	*5-N*	*5-S*	*6*
Corn									
Planting Date	4/20	4/15	4/22	4/27	4/7	3/25	4/21	4/7	4/22
Harvesting Date	9/30	9/18	9/9	9/7	8/21	8/9	9/14	8/7	9/1
Growing Season (days)	156	146	140	133	136	137	146	121	132
Cotton									
Planting Date	5/14	5/10	6/1	5/25	4/20	4/24	4/25	4/20	4/15
Harvesting Date	10/25	10/21	11/7	11/7	10/11	9/1	9/29	9/17	11/22
Growing Season (days)	164	153	157	152	154	151	157	127	207
Oats									
Planting Date	11/30	11/9	11/29	10/29	7/16	10/9	11/18	11/7	10/21
Harvesting Date	7/6	7/11	7/6	6/25	6/23	6/14	6/24	6/22	6/12
Growing Season (days)	217	245	218	239	242	248	217	227	234
Peanuts									
Planting Date	6/17	6/22	5/22	6/5	6/18	6/5	6/20	6/13	----
Harvesting Date	10/20	10/25	10/28	11/15	10/21	10/19	11/6	10/15	----
Growing Season (days)	142	136	159	146	125	135	139	124	----
Rice									
Planting Date	----	----	----	----	----	----	4/16	4/14	----
Harvesting Date	----	----	----	----	----	----	9/8	9/2	----
Growing Season (days)	----	----	----	----	----	----	145	142	----
Sorghum									
Planting Date	6/7	5/29	6/2	5/7	5/11	4/4	4/27	4/9	4/21
Harvesting Date	10/31	10/25	10/30	10/14	10/14	8/9	9/13	7/24	8/19
Growing Season (days)	145	163	157	160	156	127	140	106	120
Soybeans									
Planting Date	6/8	6/12	----	----	----	5/10	5/20	6/2	----
Harvesting Date	11/4	11/1	----	----	----	9/6	9/30	10/14	----
Growing Season (days)	150	142	----	----	----	118	133	134	----
Wheat									
Planting Date	9/22	9/27	10/2	10/6	10/9	10/20	10/24	10/22	10/13
Harvesting Date	6/27	6/25	6/19	6/19	6/18	6/14	6/23	6/22	6/20
Growing Season (days)	279	271	260	256	252	237	242	243	250

Table 13.-Growing Season for Major Texas Crops (continued).

	Zones						State	Total
	7	*8-N*	*8-S*	*9*	*10-N*	*10-S*		Average
Corn								
Planting Date	4/23	3/1	3/1	3/21	3/1	3/1	4/5	4/8
Harvesting Date	9/7	8/5	7/27	8/7	8/7	7/29	8/22	8/23
Growing Season (days)	137	137	132	139	133	136	138	137
Cotton								
Planting Date	5/15	3/10	3/1	3/1	3/1	3/1	5/1	5/3
Harvesting Date	11/1	8/20	8/16	9/2	8/19	8/13	10/9	10/11
Growing Season (days)	166	148	147	136	136	144	161	161
Oats								
Planting Date	10/30	10/14	10/15	11/14	10/29	----	11/4	11/2
Harvesting Date	6/21	6/5	5/20	6/13	6/10	----	6/22	6/19
Growing Season (days)	234	233	217	211	225	----	229	229
Peanuts								
Planting Date	6/9	6/14	----	6/9	6/13	6/14	6/13	6/13
Harvesting Date	10/23	10/23	----	11/3	11/1	10/15	10/28	10/28
Growing Season (days)	136	131	----	147	141	123	137	137
Rice								
Planting Date	----	4/9	----	4/19	----	----	4/14	4/14
Harvesting Date	----	7/30	----	8/27	----	----	8/25	8/25
Growing Season (days)	----	112	----	130	----	----	132	132
Sorghum								
Planting Date	5/2	4/4	3/19	4/1	3/26	3/19	4/23	4/22
Harvesting Date	9/4	7/28	7/16	7/25	8/2	7/15	9/4	9/2
Growing Season (days)	125	114	119	115	129	118	135	133
Soybeans								
Planting Date	5/10	5/19	----	5/30	----	5/21	5/27	5/25
Harvesting Date	9/27	10/30	----	10/6	----	11/8	10/12	10/14
Growing Season (days)	140	165	----	128	----	171	139	142
Wheat								
Planting Date	10/17	10/28	10/26	10/31	11/7	10/28	10/15	10/17
Harvesting Date	6/16	5/25	5/23	6/28	5/24	5/22	6/14	6/13
Growing Season (days)	242	210	210	240	198	206	242	240

Table 14.--Monthly Precipitation Frequency with 0.1 inches Minimum Threshold, by Station (days/mon).

	Abilene	Alice	Amarillo	Austin	Beaumont
Jan	2.34	3.45	1.55	3.77	7.48
Feb	2.83	3.27	1.66	4.15	5.38
Mar	3.07	1.55	2.45	5.00	6.29
Apr	3.55	2.27	2.69	3.77	4.19
May	4.55	5.18	4.48	6.38	5.95
Jun	4.00	4.91	6.07	5.23	6.52
Jul	3.38	4.18	4.76	3.54	8.57
Aug	3.72	4.36	5.86	2.31	7.67
Sep	4.59	7.91	3.72	4.85	7.62
Oct	4.07	3.55	2.93	5.38	5.38
Nov	2.97	3.09	2.10	4.69	5.14
Dec	2.21	2.91	1.38	3.46	6.43

	Brownsville	Brownfield	Brownwood	Childress	Clayton
Jan	3.69	5.28	3.29	2.00	0.72
Feb	2.24	3.28	4.71	4.00	1.03
Mar	1.17	1.79	3.07	3.00	1.69
Apr	1.83	2.41	5.29	3.78	2.24
May	3.34	4.21	6.21	5.56	4.55
Jun	4.21	4.72	4.43	6.44	5.24
Jul	3.24	3.90	3.71	3.56	5.79
Aug	4.52	5.34	4.86	4.11	5.38
Sep	6.79	7.93	5.86	3.78	4.10
Oct	4.41	5.10	4.14	3.56	1.86
Nov	3.07	3.90	3.21	2.78	1.66
Dec	2.62	3.79	3.57	2.67	1.17

	College Station	Corpus Christi	Crockett	Dalhart	Dallas
Jan	6.59	3.72	7.55	1.83	4.00
Feb	5.59	3.07	6.69	1.88	4.77
Mar	5.90	1.83	6.93	2.83	5.08
Apr	5.48	2.31	5.72	3.46	4.62
May	6.83	4.69	7.14	6.08	6.85
Jun	5.83	4.41	6.17	5.92	5.15
Jul	4.48	3.48	5.79	7.04	2.92
Aug	4.66	4.10	5.03	6.58	2.77
Sep	6.45	6.69	6.52	4.67	3.54
Oct	5.66	4.17	5.34	3.21	4.69
Nov	5.93	3.00	6.41	2.25	4.46
Dec	6.17	3.00	7.14	1.96	3.62

Table 14.--Monthly Precipitation Frequency with 0.1 inches Minimum Threshold, by Station (days/mon) (continued).

	Del Rio	Dumas	El Paso	Falfurrias	Friona
Jan	1.72	2.38	1.52	3.38	2.24
Feb	2.12	3.10	1.41	3.85	2.92
Mar	1.92	3.00	1.00	1.46	2.72
Apr	3.24	3.17	0.59	2.62	3.60
May	4.24	5.62	0.83	3.85	5.36
Jun	3.32	6.76	1.62	4.15	5.88
Jul	2.76	5.34	3.72	3.38	5.48
Aug	2.56	6.14	3.66	3.00	6.88
Sep	4.00	4.76	3.14	5.46	5.68
Oct	2.92	3.00	2.31	3.46	3.72
Nov	2.00	2.76	1.41	2.46	2.24
Dec	1.68	2.24	1.79	2.00	2.76

	Fort Hancock	Fort Stockton	Graham	Guthrie	Hereford
Jan	3.40	1.47	3.66	1.80	1.55
Feb	2.40	2.06	4.69	5.00	2.86
Mar	1.20	1.06	4.76	3.60	2.55
Apr	1.60	1.76	5.17	5.20	3.03
May	2.80	3.47	6.79	6.60	5.07
Jun	2.00	3.06	5.10	6.80	6.17
Jul	4.40	2.59	4.28	5.00	5.07
Aug	6.60	4.24	4.55	4.80	6.38
Sep	5.60	4.76	6.10	6.60	4.72
Oct	3.00	3.29	5.31	3.40	3.24
Nov	1.60	1.76	4.24	2.00	2.38
Dec	2.20	1.24	4.14	3.00	2.34

	Houston	Kerrville	Laredo	Llano	Lubbock
Jan	6.71	5.23	3.67	3.72	1.10
Feb	4.94	5.08	3.67	4.48	2.14
Mar	5.53	5.77	1.00	4.14	2.48
Apr	4.29	5.00	3.33	4.76	2.31
May	5.71	7.08	4.33	6.52	4.38
Jun	6.47	5.85	5.33	5.17	4.66
Jul	6.06	4.23	2.67	3.34	4.48
Aug	6.00	3.62	3.67	4.10	4.31
Sep	6.06	6.15	7.33	5.66	4.38
Oct	5.24	6.00	3.67	4.72	3.21
Nov	5.94	5.46	4.33	3.93	1.79
Dec	5.41	5.31	5.33	3.79	1.97

Table 14.–Monthly Precipitation Frequency with 0.1 inches Minimum Threshold, by Station (days/mon) (continued).

	Marshall	McAllen	Midland	Morton	Nacogdoches
Jan	8.89	4.24	1.21	2.62	7.44
Feb	6.68	3.76	1.55	3.38	7.56
Mar	7.95	1.55	1.41	2.15	7.00
Apr	7.11	2.79	1.90	3.62	5.11
May	7.16	4.76	3.21	5.54	7.44
Jun	6.74	4.38	2.86	6.00	7.22
Jul	5.89	3.31	2.83	5.23	7.11
Aug	5.58	4.69	3.38	7.00	4.78
Sep	6.79	6.31	3.97	4.38	6.11
Oct	4.74	3.97	2.86	3.62	8.00
Nov	6.53	2.90	1.41	2.77	6.22
Dec	8.05	3.72	1.41	3.38	8.22

	Pampa	Paris	Pecos	Perryton	Plainview
Jan	2.20	5.68	1.86	2.21	2.11
Feb	3.44	5.96	2.07	2.76	3.89
Mar	3.44	6.92	1.28	3.72	3.11
Apr	4.28	6.80	1.55	3.59	4.00
May	7.28	8.52	3.28	6.45	6.89
Jun	7.24	6.60	3.03	6.24	7.89
Jul	4.80	5.20	3.38	5.21	4.33
Aug	6.20	5.44	3.86	5.45	6.22
Sep	5.64	7.08	4.97	4.41	6.00
Oct	3.64	6.20	3.45	2.62	4.33
Nov	3.04	5.40	1.86	2.90	2.33
Dec	2.32	6.48	1.76	2.34	3.67

	Port Arthur	Presidio	San Angelo	San Antonio	Seymour
Jan	6.96	0.67	1.72	3.66	3.00
Feb	5.16	0.93	2.52	3.66	3.93
Mar	5.00	0.47	2.34	3.41	4.55
Apr	3.68	0.40	2.86	3.90	4.62
May	6.08	1.60	4.79	5.31	6.66
Jun	5.64	2.33	3.62	4.69	5.59
Jul	7.52	4.00	2.38	2.72	4.52
Aug	7.44	3.93	3.38	3.62	5.31
Sep	7.24	3.67	4.62	4.83	5.45
Oct	4.80	1.93	3.52	4.66	5.07
Nov	5.56	1.07	2.38	3.79	3.28
Dec	6.16	0.60	1.93	3.17	3.86

Table 14.--Monthly Precipitation Frequency with 0.1 inches Minimum Threshold, by Station (days/mon) (continued).

	Sherman	Snyder	Sonora	Stephenville	Temple
Jan	4.31	2.04	2.24	2.11	5.73
Feb	5.38	2.35	2.53	3.89	6.55
Mar	6.55	1.78	1.53	3.11	4.36
Apr	6.79	2.61	3.29	4.00	5.73
May	7.62	4.09	4.41	6.89	6.73
Jun	6.90	4.00	3.41	7.89	4.45
Jul	4.48	2.78	3.65	4.33	3.45
Aug	4.59	3.43	4.18	6.22	4.09
Sep	6.00	4.61	5.12	6.00	6.55
Oct	5.62	3.83	4.00	4.33	4.27
Nov	5.14	2.17	2.47	2.33	4.91
Dec	4.97	1.87	1.53	3.67	5.64

	Texarkana	Tulia	Tyler	Uvalde	Van Horn
Jan	6.53	2.03	7.05	2.52	2.14
Feb	6.24	3.14	6.45	2.71	1.71
Mar	6.59	3.07	7.09	1.95	1.71
Apr	6.24	3.93	6.95	3.81	1.57
May	7.18	5.97	7.41	4.76	2.43
Jun	6.12	6.69	6.18	3.57	4.00
Jul	5.76	4.93	4.82	2.48	5.71
Aug	4.06	6.31	4.18	3.43	6.00
Sep	5.53	5.41	5.86	4.67	5.71
Oct	6.24	3.83	4.86	3.76	2.57
Nov	6.47	2.69	6.09	2.62	2.43
Dec	6.12	2.62	6.82	2.05	2.00

	Victoria	Waco	Wichita Falls
Jan	4.60	3.66	2.10
Feb	4.08	4.00	3.34
Mar	3.40	4.03	3.90
Apr	3.04	4.52	4.79
May	5.16	5.59	6.24
Jun	5.44	4.97	4.59
Jul	4.80	2.38	2.86
Aug	5.20	3.21	4.07
Sep	6.64	4.45	4.93
Oct	4.56	4.45	4.17
Nov	4.00	4.38	2.86
Dec	4.04	3.76	2.69

Table 15.-Wetness Factor (FW) for Adjusting for Surface Wetness

Number per Month of Wet Event	Texture of Soil					
	Clay	Clay Loam	Silt Loam	Sandy Loam	Loamy Sand	Sand
1.00	0.130	0.097	0.075	0.064	0.054	0.043
1.25	0.162	0.121	0.094	0.080	0.067	0.054
1.50	0.195	0.145	0.113	0.096	0.080	0.065
1.75	0.228	0.170	0.131	0.112	0.093	0.076
2.00	0.260	0.194	0.150	0.128	0.107	0.086
2.25	0.292	0.218	0.169	0.144	0.121	0.097
2.50	0.325	0.242	0.188	0.161	0.134	0.108
2.75	0.357	0.266	0.206	0.176	0.147	0.119
3.00	0.389	0.291	0.225	0.193	0.161	0.129
3.25	0.418	0.315	0.244	0.209	0.174	0.140
3.50	0.443	0.339	0.263	0.225	0.187	0.151
3.75	0.467	0.363	0.281	0.241	0.201	0.162
4.00	0.487	0.387	0.300	0.257	0.214	0.173
4.25	0.508	0.411	0.319	0.272	0.227	0.183
4.50	0.525	0.432	0.338	0.289	0.241	0.194
4.75	0.541	0.452	0.356	0.305	0.254	0.204
5.00	0.558	0.472	0.375	0.321	0.268	0.215
5.25	0.571	0.488	0.394	0.337	0.281	0.226
5.50	0.585	0.504	0.412	0.353	0.294	0.237
5.75	0.598	0.519	0.431	0.369	0.308	0.248
6.00	0.611	0.535	0.450	0.385	0.321	0.259
6.25	0.621	0.547	0.464	0.401	0.325	0.270
6.50	0.631	0.559	0.479	0.417	0.348	0.280
6.75	0.641	0.572	0.493	0.434	0.362	0.291
7.00	0.652	0.584	0.507	0.450	0.375	0.302
7.25	0.662	0.596	0.522	0.466	0.389	0.312
7.50	0.672	0.608	0.530	0.482	0.402	0.323
7.75	0.679	0.617	0.546	0.494	0.415	0.334
8.00	0.687	0.626	0.557	0.505	0.429	0.345
8.25	0.694	0.634	0.567	0.517	0.442	0.355
8.50	0.702	0.643	0.578	0.528	0.455	0.366
8.75	0.709	0.652	0.588	0.540	0.469	0.377
9.00	0.716	0.661	0.598	0.552	0.482	0.388
9.25	0.724	0.670	0.609	0.563	0.495	0.399
9.50	0.731	0.678	0.619	0.575	0.508	0.409
9.75	0.739	0.687	0.630	0.586	0.522	0.420
10.00	0.746	0.696	0.640	0.598	0.535	0.431
10.25	0.751	0.702	0.647	0.606	0.544	0.442
10.50	0.756	0.708	0.654	0.613	0.553	0.453
10.75	0.760	0.713	0.660	0.621	0.561	0.463
11.00	0.765	0.719	0.667	0.628	0.570	0.474
11.25	0.770	0.725	0.674	0.636	0.579	0.485
11.50	0.775	0.730	0.681	0.644	0.588	0.496
11.75	0.780	0.736	0.688	0.651	0.597	0.506
12.00	0.784	0.742	0.694	0.659	0.605	0.517
15.00	0.842	0.811	0.776	0.750	0.711	0.646
30.00	1.000	1.000	1.000	1.000	1.000	1.000

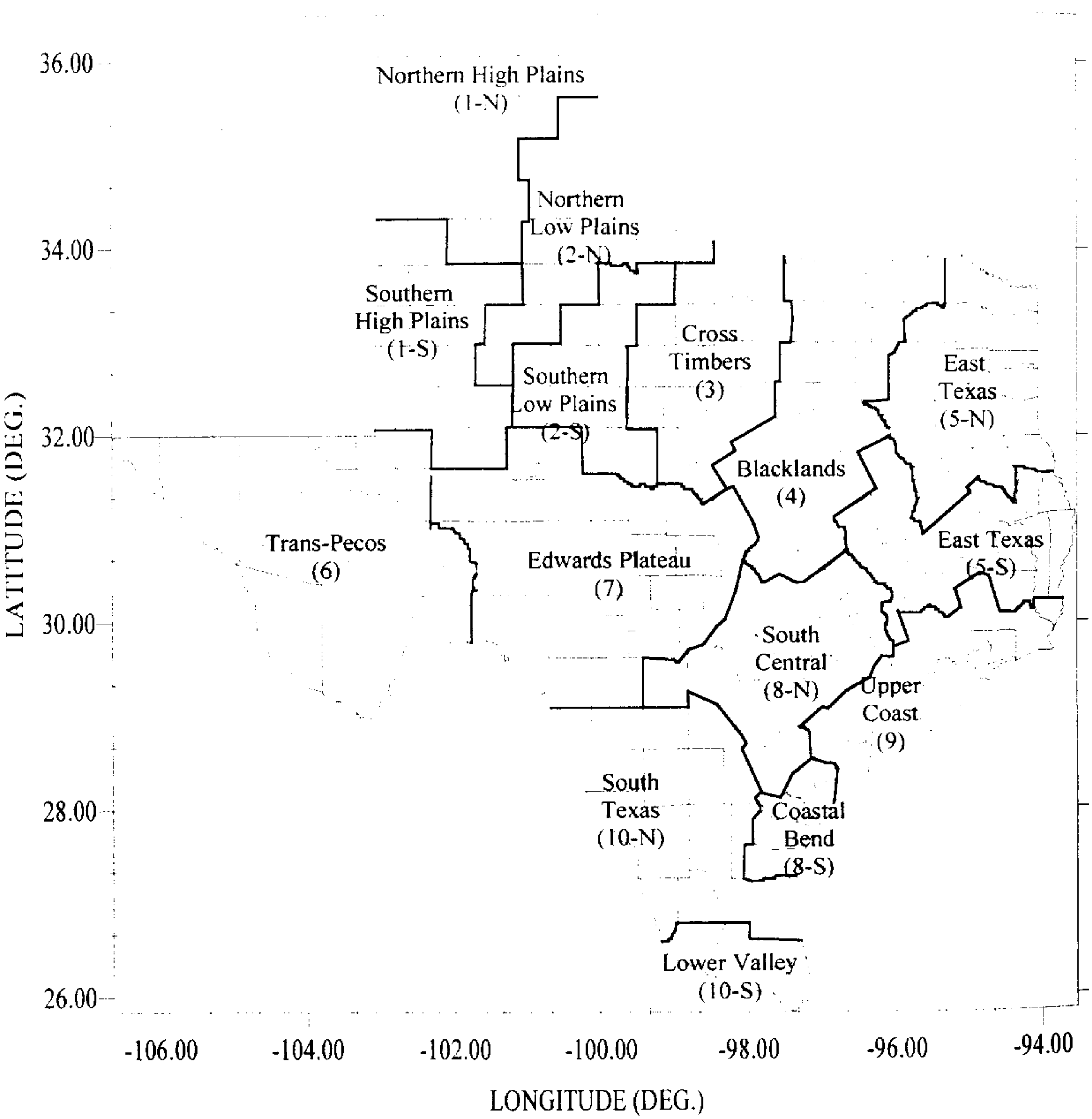


Figure 29.-Texas Crop Reporting Districts.

Table 16.-Crop Evapotranspiration (ET_{crop}) for Crops in Texas (inches per month).

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Northern High Plains (1-N)								
Dumas								
Corn	0.00	0.00	0.00	1.44	5.44	7.29	9.65	8.57
Oats	1.63	2.84	4.78	6.52	7.03	6.36	0.85	0.00
Sorghum	0.00	0.00	0.00	0.00	0.00	4.41	7.37	8.15
Soybeans	0.00	0.00	0.00	0.00	0.00	4.36	7.78	8.22
Winter Wheat	2.55	2.90	4.76	6.33	6.26	5.48	0.00	0.00
Hereford								
Corn	0.00	0.00	0.00	1.19	5.29	7.34	9.35	8.34
Cotton	0.00	0.00	0.00	0.00	2.69	6.16	7.49	8.07
Peanuts	0.00	0.00	0.00	0.00	2.36	5.67	7.80	7.67
Sorghum	0.00	0.00	0.00	0.00	0.00	4.34	7.12	7.92
Soybeans	0.00	0.00	0.00	0.00	0.00	4.16	7.25	8.00
Winter Wheat	2.74	3.11	5.06	6.58	6.24	5.26	0.00	0.00
Southern High Plains (1-S)								
Brownfield								
Corn	0.00	0.00	0.00	1.72	5.72	7.95	9.61	8.17
Cotton	0.00	0.00	0.00	0.00	3.28	6.25	7.75	8.61
Peanuts	0.00	0.00	0.00	0.00	2.96	5.66	8.11	7.96
Sorghum	0.00	0.00	0.00	0.00	0.45	5.89	7.76	8.36
Soybeans	0.00	0.00	0.00	0.00	0.00	3.28	7.12	8.31
Winter Wheat	3.06	3.57	5.73	7.07	6.44	4.45	0.00	0.00
Lubbock								
Corn	0.00	0.00	0.00	1.57	5.31	7.47	8.90	7.66
Cotton	0.00	0.00	0.00	0.00	3.11	5.87	7.22	8.01
Peanuts	0.00	0.00	0.00	0.00	2.83	5.27	7.52	7.43
Sorghum	0.00	0.00	0.00	0.00	0.42	5.54	7.23	7.80
Soybeans	0.00	0.00	0.00	0.00	0.00	3.07	6.68	7.75
Winter Wheat	2.79	3.27	5.36	6.51	6.02	4.15	0.00	0.00
Northern Low Plains (2-N)								
Childress								
Corn	0.00	0.00	0.00	1.05	5.35	7.53	9.83	7.97
Cotton	0.00	0.00	0.00	0.00	0.00	5.86	6.94	7.67
Peanuts	0.00	0.00	0.00	0.00	1.51	5.91	7.63	8.20
Sorghum	0.00	0.00	0.00	0.00	0.00	5.29	7.56	8.59
Winter Wheat	2.76	3.14	5.13	6.32	5.90	3.47	0.00	0.00

Table 16.-Crop Evapotranspiration (ET_{crop}) for Crops in Texas (inches per month) (continued).

Location	Sep	Oct	Nov	Dec	Total	Date of Planting	Growing Season (days)
Northern High Plains (1-N)							
Dumas							
Corn	5.29	0.00	0.00	0.00	37.68	4/20	163
Oats	0.00	0.00	0.04	0.93	31.00	11/29	217
Sorghum	6.16	3.69	0.00	0.00	29.78	6/6	145
Soybeans	6.24	4.41	0.34	0.00	31.34	6/7	150
Winter Wheat	1.30	2.95	1.94	2.23	36.70	9/21	279
Hereford							
Corn	5.17	0.00	0.00	0.00	36.68	4/20	163
Cotton	6.69	3.76	0.00	0.00	34.86	5/14	164
Peanuts	5.78	2.68	0.00	0.00	31.96	5/15	158
Sorghum	6.12	3.81	0.00	0.00	29.31	6/6	145
Soybeans	6.20	4.46	0.32	0.00	30.38	6/7	150
Winter Wheat	1.24	2.66	2.01	2.43	37.33	9/22	279
Southern High Plains (1-S)							
Brownfield							
Corn	3.27	0.00	0.00	0.00	36.44	4/15	156
Cotton	7.01	3.29	0.00	0.00	36.19	5/10	164
Peanuts	6.07	2.89	0.44	0.00	34.09	5/10	163
Sorghum	6.27	3.61	0.00	0.00	32.34	5/29	149
Soybeans	6.51	4.67	0.08	0.00	29.97	6/11	142
Winter Wheat	0.64	3.29	2.37	2.81	39.44	9/27	271
Lubbock							
Corn	2.81	0.00	0.00	0.00	33.72	4/15	156
Cotton	6.40	2.94	0.00	0.00	33.55	5/10	164
Peanuts	5.57	2.55	0.00	0.00	31.17	5/10	163
Sorghum	5.74	3.18	0.00	0.00	29.91	5/29	149
Soybeans	5.96	4.15	0.06	0.00	27.65	6/11	142
Winter Wheat	0.53	2.54	1.80	2.43	35.39	9/27	271
Northern Low Plains (2-N)							
Childress							
Corn	1.42	0.00	0.00	0.00	33.14	4/21	140
Cotton	6.98	5.54	0.97	0.00	33.96	6/1	163
Peanuts	6.17	3.75	0.00	0.00	33.18	5/21	159
Sorghum	6.40	4.19	0.42	0.00	32.45	6/2	150
Winter Wheat	0.00	2.74	1.84	2.34	33.64	10/2	260

Table 16.-Crop Evapotranspiration (ET_{crop}) for Crops in Texas (inches per month) (continued).

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Guthrie								
Corn	0.00	0.00	0.00	1.23	5.72	7.82	10.09	8.25
Cotton	0.00	0.00	0.00	0.00	0.00	6.18	7.41	7.93
Peanuts	0.00	0.00	0.00	0.00	1.65	6.22	8.02	8.44
Sorghum	0.00	0.00	0.00	0.00	0.00	5.58	7.96	8.84
Winter Wheat	3.03	3.36	5.40	6.63	6.23	3.65	0.00	0.00
Southern Low Plains (2-S)								
Snyder								
Corn	0.00	0.00	0.00	0.43	5.41	7.43	9.66	8.03
Cotton	0.00	0.00	0.00	0.00	1.04	5.49	6.92	7.88
Peanuts	0.00	0.00	0.00	0.00	0.00	4.11	6.28	7.82
Sorghum	0.00	0.00	0.00	0.00	3.72	6.32	8.83	8.65
Winter Wheat	3.02	3.55	5.59	6.78	6.18	2.99	0.00	0.00
Abilene								
Corn	0.00	0.00	0.00	0.47	5.04	7.18	9.41	8.06
Cotton	0.00	0.00	0.00	0.00	1.72	8.38	9.35	8.95
Peanuts	0.00	0.00	0.00	0.00	0.00	3.98	6.33	7.87
Sorghum	0.00	0.00	0.00	0.00	0.00	1.38	5.80	7.33
Winter Wheat	2.90	3.15	5.20	6.42	5.72	2.90	0.00	0.00
Cross Timbers (3)								
Stephenville								
Corn	0.00	0.00	0.00	2.62	5.40	7.78	9.05	4.86
Cotton	0.00	0.00	0.00	1.20	4.50	6.34	8.22	9.24
Peanuts	0.00	0.00	0.00	0.00	0.00	2.30	6.32	7.93
Sorghum	0.00	0.00	0.00	0.00	2.98	6.10	8.38	8.59
Winter Wheat	2.74	3.11	4.97	5.74	5.33	3.22	0.00	0.00
Graham								
Corn	0.00	0.00	0.00	3.01	5.68	8.12	9.44	4.89
Cotton	0.00	0.00	0.00	1.38	4.73	6.35	8.57	9.57
Peanuts	0.00	0.00	0.00	0.00	0.00	2.11	6.58	8.17
Sorghum	0.00	0.00	0.00	0.00	3.13	6.02	8.74	8.90
Winter Wheat	2.83	3.22	5.08	6.05	5.59	2.94	0.00	0.00
Blacklands (4)								
Sherman								
Corn	0.00	0.00	0.64	4.02	5.62	7.48	8.00	1.82
Cotton	0.00	0.00	0.00	0.85	4.44	6.28	8.97	8.11
Peanuts	0.00	0.00	0.00	0.00	0.00	4.21	6.70	7.79
Sorghum	0.00	0.00	0.00	3.32	5.44	7.14	7.82	1.75
Soybeans	0.00	0.00	0.00	0.00	3.05	6.40	8.48	7.51
Winter Wheat	2.44	2.87	4.48	5.42	5.05	2.26	0.00	0.00

Table 16.-Crop Evapotranspiration (ET_{crop}) for Crops in Texas (inches per month) (continued).

Location	Sep	Oct	Nov	Dec	Total	Date of Planting	Growing Season (days)
Guthrie							
Corn	1.61	0.00	0.00	0.00	34.72	4/21	140
Cotton	7.15	5.70	1.05	0.00	35.42	6/1	163
Peanuts	6.38	3.88	0.00	0.00	34.59	5/21	159
Sorghum	6.62	4.35	0.00	0.00	33.35	6/2	150
Winter Wheat	0.00	2.79	1.90	2.57	35.55	10/2	260
Southern Low Plains (2-S)							
Snyder							
Corn	1.47	0.00	0.00	0.00	32.43	4/27	135
Cotton	6.91	5.32	0.63	0.00	34.19	5/25	166
Peanuts	6.16	4.78	1.27	0.00	30.42	6/5	163
Sorghum	5.88	1.68	0.00	0.00	35.09	5/6	160
Winter Wheat	0.00	2.45	1.77	2.54	34.87	10/6	256
Abilene							
Corn	1.50	0.00	0.00	0.00	31.66	4/27	135
Cotton	6.84	5.11	0.73	0.00	41.09	5/25	166
6.29	4.74	1.27	0.00	0.00	30.48	6/5	163
Sorghum	6.29	4.77	1.28	0.00	26.84	5/6	160
Winter Wheat	0.00	2.49	1.88	2.29	32.94	10/6	256
Cross Timbers (3)							
Stephenville							
Corn	0.00	0.00	0.00	0.00	29.71	4/6	136
Cotton	6.95	1.46	0.00	0.00	37.91	4/20	174
Peanuts	6.26	2.72	0.00	0.00	25.53	6/17	125
Sorghum	6.03	1.65	0.00	0.00	33.73	5/10	156
Winter Wheat	0.00	2.15	1.70	2.33	31.28	10/9	252
Graham							
Corn	0.00	0.00	0.00	0.00	31.13	4/6	136
Cotton	7.11	1.59	0.00	0.00	39.30	4/20	174
Peanuts	6.39	2.98	0.00	0.00	26.23	6/17	125
Sorghum	6.16	1.83	0.00	0.00	34.77	5/10	156
Winter Wheat	0.00	2.47	2.09	2.41	32.70	10/9	252
Blacklands (4)							
Sherman							
Corn	0.00	0.00	0.00	0.00	27.57	3/24	137
Cotton	0.16	0.00	0.00	0.00	28.81	4/24	130
Peanuts	5.73	2.21	0.00	0.00	26.65	6/4	135
Sorghum	0.00	0.00	0.00	0.00	25.46	4/3	127
Soybeans	0.74	0.00	0.00	0.00	26.18	5/9	118
Winter Wheat	0.00	1.16	1.82	1.93	27.43	10/20	237

Table 16.-Crop Evapotranspiration (ET_{crop}) for Crops in Texas (inches per month) (continued).

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Waco								
Corn	0.00	0.00	0.59	3.80	5.79	7.91	8.32	1.84
Cotton	0.00	0.00	0.00	0.76	4.30	6.58	9.46	8.80
Peanuts	0.00	0.00	0.00	0.00	0.00	4.11	6.59	8.45
Sorghum	0.00	0.00	0.00	2.95	5.56	7.55	8.07	1.75
Soybeans	0.00	0.00	0.00	0.00	2.92	6.73	8.92	8.06
Winter Wheat	2.69	3.09	4.78	5.38	5.00	2.16	0.00	0.00
East Texas (5-N)								
Texarkana								
Corn	0.00	0.00	0.00	1.16	4.57	6.06	7.62	6.70
Cotton	0.00	0.00	0.00	0.70	4.19	5.46	6.92	7.46
Peanuts	0.00	0.00	0.00	0.00	0.00	1.60	5.35	6.28
Sorghum	0.00	0.00	0.00	0.46	4.51	5.96	7.27	6.52
Soybeans	0.00	0.00	0.00	0.00	1.59	5.20	7.13	6.99
Winter Wheat	2.25	2.92	4.34	5.36	5.16	3.48	0.00	0.00
Nacogdoches								
Corn	0.00	0.00	0.00	1.07	4.66	6.11	7.43	6.61
Cotton	0.00	0.00	0.00	0.64	4.30	5.57	6.78	7.33
Peanuts	0.00	0.00	0.00	0.00	0.00	1.68	5.46	6.23
Sorghum	0.00	0.00	0.00	0.43	4.60	6.02	7.09	6.45
Soybeans	0.00	0.00	0.00	0.00	1.64	5.33	6.95	6.88
Winter Wheat	2.32	2.88	4.43	5.26	5.24	3.64	0.00	0.00
East Texas (5-S)								
College Station								
Corn	0.00	0.00	0.00	2.69	5.32	7.16	7.33	1.28
Cotton	0.00	0.00	0.00	1.23	4.34	5.89	7.78	7.96
Peanuts	0.00	0.00	0.00	0.00	0.00	2.68	5.91	7.06
Sorghum	0.00	0.00	0.00	2.49	5.48	6.81	4.92	0.00
Soybeans	0.00	0.00	0.00	0.00	0.00	4.42	7.04	7.45
Winter Wheat	2.69	3.15	4.70	5.37	5.22	3.43	0.00	0.00
Trans-Pecos (6)								
El Paso								
Corn	0.00	0.00	0.00	0.77	5.00	8.78	9.58	7.10
Cotton	0.00	0.00	0.00	1.36	3.76	7.11	8.41	8.77
Sorghum	0.00	0.00	0.00	0.85	5.45	9.33	8.84	3.71
Winter Wheat	3.19	4.00	6.19	7.51	6.17	2.60	0.00	0.00
Presidio								
Corn	0.00	0.00	0.00	0.89	6.21	9.79	10.64	8.53
Cotton	0.00	0.00	0.00	1.57	6.10	8.14	9.41	10.42
Sorghum	0.00	0.00	0.00	0.98	6.66	10.29	9.81	4.47
Winter Wheat	4.51	5.39	8.03	9.17	7.31	3.28	0.00	0.00

Table 16.-Crop Evapotranspiration (ET_{crop}) for Crops in Texas (inches per month) (continued).

Location	Sep	Oct	Nov	Dec	Total	Date of Planting	Growing Season (days)
Waco							
Corn	0.00	0.00	0.00	0.00	28.25	3/24	137
Cotton	0.17	0.00	0.00	0.00	30.07	4/24	130
Peanuts	6.29	2.44	0.00	0.00	27.87	6/4	135
Sorghum	0.00	0.00	0.00	0.00	25.89	4/3	127
Soybeans	0.75	0.00	0.00	0.00	27.38	5/9	118
Winter Wheat	0.00	1.16	1.91	2.11	28.28	10/20	237
East Texas (5-N)							
Texarkana							
Corn	2.06	0.00	0.00	0.00	28.17	4/20	146
Cotton	5.04	0.00	0.00	0.00	29.77	4/25	157
Peanuts	5.26	3.89	0.48	0.00	22.86	6/19	139
Sorghum	1.99	0.00	0.00	0.00	26.72	4/26	140
Soybeans	4.69	0.00	0.00	0.00	25.60	5/19	133
Winter Wheat	0.00	0.73	1.96	1.80	27.99	10/24	242
Nacogdoches							
Corn	2.16	0.00	0.00	0.00	28.03	4/20	146
Cotton	5.20	0.00	0.00	0.00	29.82	4/25	157
Peanuts	5.43	4.05	0.49	0.00	23.33	6/19	139
Sorghum	2.09	0.00	0.00	0.00	26.67	4/26	140
Soybeans	4.88	0.00	0.00	0.00	25.68	5/19	133
Winter Wheat	0.00	0.81	1.96	2.03	28.57	10/24	242
East Texas (5-S)							
College Station							
Corn	0.00	0.00	0.00	0.00	23.78	4/7	122
Cotton	3.06	0.00	0.00	0.00	30.26	4/20	150
Peanuts	5.60	1.88	0.00	0.00	23.12	6/12	124
Sorghum	0.00	0.00	0.00	0.00	19.69	4/8	106
Soybeans	5.63	1.66	0.00	0.00	26.20	6/1	134
Winter Wheat	0.00	0.99	2.11	2.25	29.92	10/22	243
Trans-Pecos (6)							
El Paso							
Corn	0.15	0.00	0.00	0.00	31.38	4/21	132
Cotton	7.18	1.33	0.00	0.00	37.92	4/15	178
Sorghum	0.00	0.00	0.00	0.00	28.18	4/20	120
Winter Wheat	0.00	1.52	1.49	2.24	34.90	10/13	250
Presidio							
Corn	0.18	0.00	0.00	0.00	36.25	4/21	132
Cotton	8.51	1.68	0.00	0.00	45.83	4/15	178
Sorghum	0.00	0.00	0.00	0.00	32.21	4/20	120
Winter Wheat	0.00	1.80	1.94	3.23	44.67	10/13	250

Table 16.-Crop Evapotranspiration (ET_{crop}) for Crops in Texas (inches per month) (continued).

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Pecos								
Corn	0.00	0.00	0.00	1.02	6.38	9.20	10.58	8.17
Cotton	0.00	0.00	0.00	1.81	5.44	7.81	9.37	10.01
Sorghum	0.00	0.00	0.00	1.13	6.71	9.66	9.75	4.28
Winter Wheat	3.78	4.54	7.05	8.39	7.23	3.33	0.00	0.00
Edwards Plateau (7)								
Sonora								
Corn	0.00	0.00	0.00	0.96	5.19	7.46	9.46	7.99
Cotton	0.00	0.00	0.00	0.00	2.23	5.40	7.30	8.42
Peanuts	0.00	0.00	0.00	0.00	0.00	3.21	6.60	8.12
Sorghum	0.00	0.00	0.00	0.00	4.35	7.21	9.04	7.65
Soybeans	0.00	0.00	0.00	0.00	3.10	6.59	9.04	8.67
Winter Wheat	3.61	4.13	6.18	6.83	5.73	2.28	0.00	0.00
Kerrville								
Corn	0.00	0.00	0.00	0.95	4.84	6.63	8.62	7.45
Cotton	0.00	0.00	0.00	0.00	1.97	5.25	6.80	7.81
Peanuts	0.00	0.00	0.00	0.00	0.00	3.42	6.21	7.59
Sorghum	0.00	0.00	0.00	0.00	4.30	6.46	8.22	7.11
Soybeans	0.00	0.00	0.00	0.00	3.10	6.04	8.22	8.03
Winter Wheat	3.10	3.46	5.23	5.73	5.23	2.51	0.00	0.00
South Central (8-N)								
Austin								
Corn	0.00	0.00	2.84	4.27	5.82	6.95	7.30	0.80
Cotton	0.00	0.00	1.84	3.50	5.09	7.01	8.44	2.02
Peanuts	0.00	0.00	0.00	0.00	0.00	2.41	5.76	6.98
Sorghum	0.00	0.00	0.00	2.79	5.24	6.62	5.65	0.00
Soybeans	0.00	0.00	0.00	0.00	1.63	4.93	7.51	7.53
Winter Wheat	2.94	3.16	4.72	4.86	3.45	0.00	0.00	0.00
San Antonio								
Corn	0.00	0.00	2.68	4.46	6.44	7.46	7.31	0.92
Cotton	0.00	0.00	1.66	3.76	5.56	7.50	8.51	2.21
Peanuts	0.00	0.00	0.00	0.00	0.00	2.46	5.60	7.48
Sorghum	0.00	0.00	0.00	3.00	5.75	7.11	5.55	0.00
Soybeans	0.00	0.00	0.00	0.00	1.69	5.18	7.54	8.02
Winter Wheat	3.06	3.52	5.19	5.18	3.63	0.00	0.00	0.00
Coastal Bend (8-S)								
Corpus Christi								
Corn	0.00	0.00	2.04	4.24	6.10	6.86	5.78	0.00
Cotton	0.00	0.00	1.74	3.39	5.35	6.99	7.78	1.64
Sorghum	0.00	0.00	0.84	3.76	5.77	6.38	3.22	0.00
Winter Wheat	2.94	3.26	4.79	4.72	3.02	0.00	0.00	0.00

Table 16.-Crop Evapotranspiration (ET_{crop}) for Crops in Texas (inches per month) (continued).

Location	Sep	Oct	Nov	Dec	Total	Date of Planting	Growing Season (days)
Pecos							
Corn	0.18	0.00	0.00	0.00	35.53	4/21	132
Cotton	8.00	1.60	0.00	0.00	44.04	4/15	178
Sorghum	0.00	0.00	0.00	0.00	31.53	4/20	120
Winter Wheat	0.00	2.02	1.90	2.89	41.12	10/13	250
Edwards Plateau (7)							
Sonora							
Corn	1.20	0.00	0.00	0.00	32.26	4/22	137
Cotton	7.31	5.34	0.00	0.00	36.00	5/15	166
Peanuts	6.43	3.35	0.00	0.00	27.70	6/8	136
Sorghum	0.65	0.00	0.00	0.00	28.90	5/1	125
Soybeans	4.99	0.00	0.00	0.00	32.37	5/9	140
Winter Wheat	0.00	1.56	1.80	2.59	34.69	10/17	242
Kerrville							
Corn	1.14	0.00	0.00	0.00	29.62	4/22	137
Cotton	6.67	4.86	0.00	0.00	33.36	5/15	166
Peanuts	5.89	3.19	0.00	0.00	26.30	6/8	136
Sorghum	0.62	0.00	0.00	0.00	26.72	5/1	125
Soybeans	4.66	0.00	0.00	0.00	30.06	5/9	140
Winter Wheat	0.00	1.62	2.27	2.52	31.66	10/17	242
South Central (8-N)							
Austin							
Corn	0.00	0.00	0.00	0.00	27.98	3/1	157
Cotton	1.65	0.00	0.00	0.00	29.55	3/10	153
Peanuts	5.86	2.81	0.00	0.00	23.82	6/13	131
Sorghum	0.00	0.00	0.00	0.00	20.30	4/3	114
Soybeans	6.14	3.75	0.00	0.00	31.49	5/18	165
Winter Wheat	0.00	0.37	1.76	1.97	23.25	10/28	210
San Antonio							
Corn	0.00	0.00	0.00	0.00	29.27	3/1	157
Cotton	1.71	0.00	0.00	0.00	30.91	3/10	153
Peanuts	6.06	3.11	0.00	0.00	24.71	6/13	131
Sorghum	0.00	0.00	0.00	0.00	21.40	4/3	114
Soybeans	6.35	4.14	0.00	0.00	32.93	5/18	165
Winter Wheat	0.00	0.40	1.83	2.22	25.02	10/28	210
Coastal Bend (8-S)							
Corpus Christi							
Corn	0.00	0.00	0.00	0.00	25.02	3/1	148
Cotton	0.00	0.00	0.00	0.00	26.89	3/1	160
Sorghum	0.00	0.00	0.00	0.00	19.97	3/18	119
Winter Wheat	0.00	0.58	1.70	2.30	23.31	10/26	210

Table 16.-Crop Evapotranspiration (ET_{crop}) for Crops in Texas (inches per month) (continued).

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Upper Coast (9)								
Houston								
Corn	0.00	0.00	0.99	3.76	5.78	6.99	6.76	1.28
Cotton	0.00	0.00	2.62	3.79	5.58	7.05	7.36	1.61
Peanuts	0.00	0.00	0.00	0.00	0.00	3.36	5.60	6.68
Sorghum	0.00	0.00	0.00	3.27	5.71	6.63	4.90	0.00
Soybeans	0.00	0.00	0.00	0.00	0.26	5.07	6.76	7.09
Winter Wheat	2.56	2.96	4.54	5.50	5.49	4.52	0.00	0.00
South Texas (10-N)								
Laredo								
Corn	0.00	0.00	2.23	5.14	7.50	8.45	8.18	1.64
Cotton	0.00	0.00	1.86	4.39	6.51	8.45	9.52	4.86
Peanuts	0.00	0.00	0.00	0.00	0.00	3.10	6.03	8.11
Sorghum	0.00	0.00	0.43	4.43	6.91	8.06	7.71	0.38
Winter Wheat	3.53	4.23	6.17	5.99	3.72	0.00	0.00	0.00
Lower Valley (10-S)								
McAllen								
Corn	0.00	0.00	2.28	4.88	6.98	7.62	6.39	0.00
Cotton	0.00	0.00	1.95	4.00	6.04	7.69	8.68	2.71
Peanuts	0.00	0.00	0.00	0.00	0.00	2.51	6.05	6.94
Sorghum	0.00	0.00	0.94	4.45	6.62	7.00	2.92	0.00
Soybeans	0.00	0.00	0.00	0.00	1.49	5.24	7.54	7.29
Winter Wheat	3.37	3.87	5.59	5.38	3.15	0.00	0.00	0.00
Brownsville								
Corn	0.00	0.00	1.95	4.46	6.75	7.27	6.00	0.00
Cotton	0.00	0.00	1.62	3.49	5.75	7.32	8.12	2.80
Peanuts	0.00	0.00	0.00	0.00	0.00	2.36	5.69	7.18
Sorghum	0.00	0.00	0.80	4.00	6.41	6.69	2.74	0.00
Soybeans	0.00	0.00	0.00	0.00	1.26	4.96	7.08	7.52
Winter Wheat	3.17	3.55	5.14	5.00	2.73	0.00	0.00	0.00

Table 16.-Crop Evapotranspiration (ET_{crop}) for Crops in Texas (inches per month) (continued).

Location	Sep	Oct	Nov	Dec	Total	Date of Planting	Growing Season (days)
Upper Coast (9)							
Houston							
Corn	0.00	0.00	0.00	0.00	25.56	3/20	139
Cotton	0.32	0.00	0.00	0.00	28.33	3/1	160
Peanuts	5.72	4.20	0.25	0.00	25.80	6/8	147
Sorghum	0.00	0.00	0.00	0.00	20.51	3/31	115
Soybeans	5.50	0.54	0.00	0.00	25.22	5/29	128
Winter Wheat	0.00	0.10	2.04	1.86	29.55	10/31	240
South Texas (10-N)							
Laredo							
Corn	0.00	0.00	0.00	0.00	33.14	3/1	160
Cotton	0.00	0.00	0.00	0.00	35.59	3/1	171
Peanuts	6.80	5.23	0.10	0.00	29.37	6/12	141
Sorghum	0.00	0.00	0.00	0.00	27.91	3/25	129
Winter Wheat	0.00	0.00	1.89	2.64	28.17	10/8	198
Lower Valley (10-S)							
McAllen							
Corn	0.00	0.00	0.00	0.00	28.15	3/1	150
Cotton	0.00	0.00	0.00	0.00	31.07	3/1	165
Peanuts	6.31	2.14	0.00	0.00	23.95	6/13	123
Sorghum	0.00	0.00	0.00	0.00	21.93	3/18	118
Soybeans	6.61	5.14	0.69	0.00	34.00	5/20	171
Winter Wheat	0.00	0.43	1.89	2.67	26.35	10/28	206
Brownsville							
Corn	0.00	0.00	0.00	0.00	26.43	3/1	150
Cotton	0.00	0.00	0.00	0.00	29.10	3/1	165
Peanuts	5.91	2.01	0.00	0.00	23.16	6/13	123
Sorghum	0.00	0.00	0.00	0.00	20.64	3/18	118
Soybeans	6.18	4.82	0.65	0.00	32.47	5/20	171
Winter Wheat	0.00	0.41	1.82	2.41	24.23	10/28	206

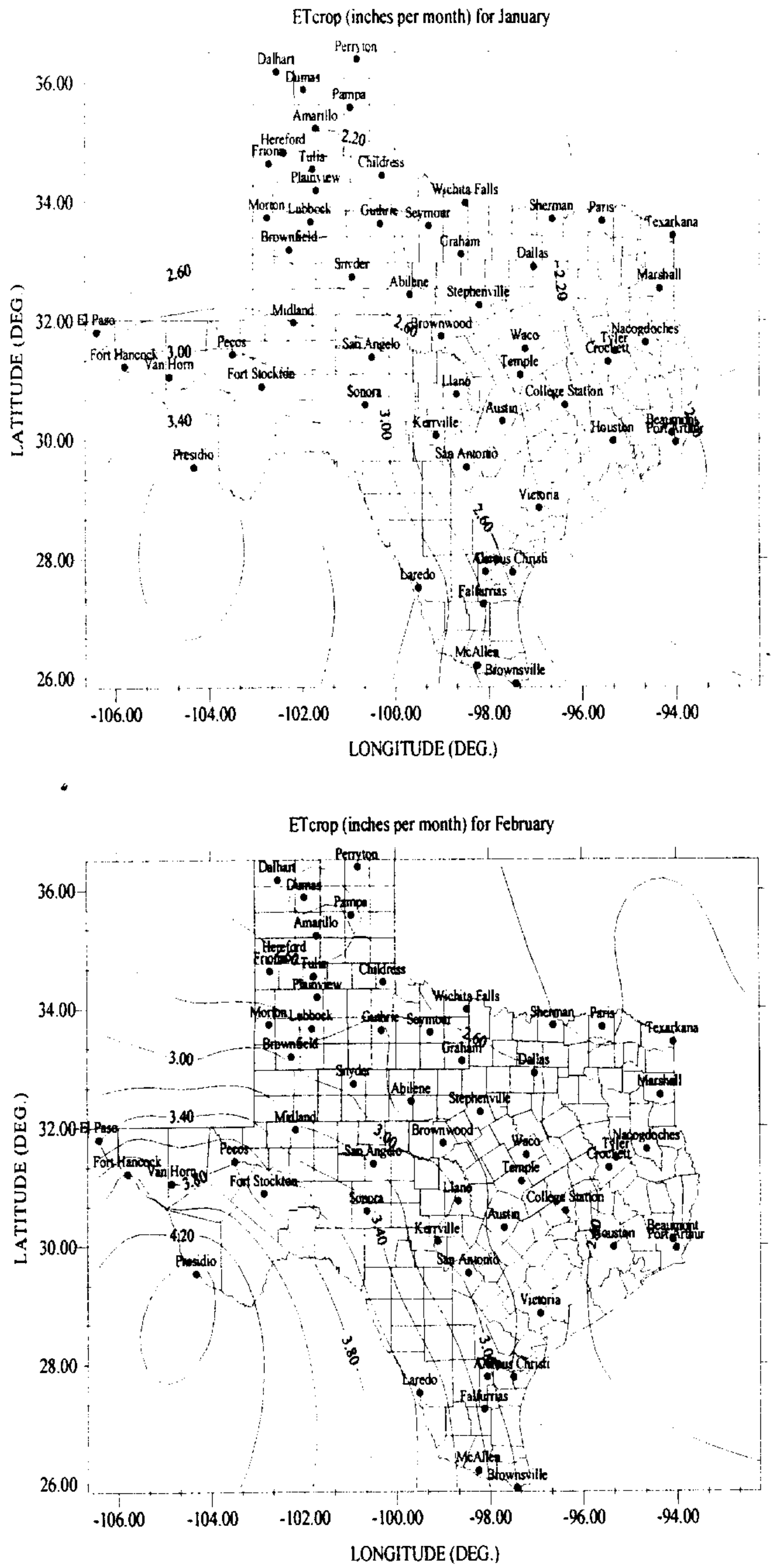
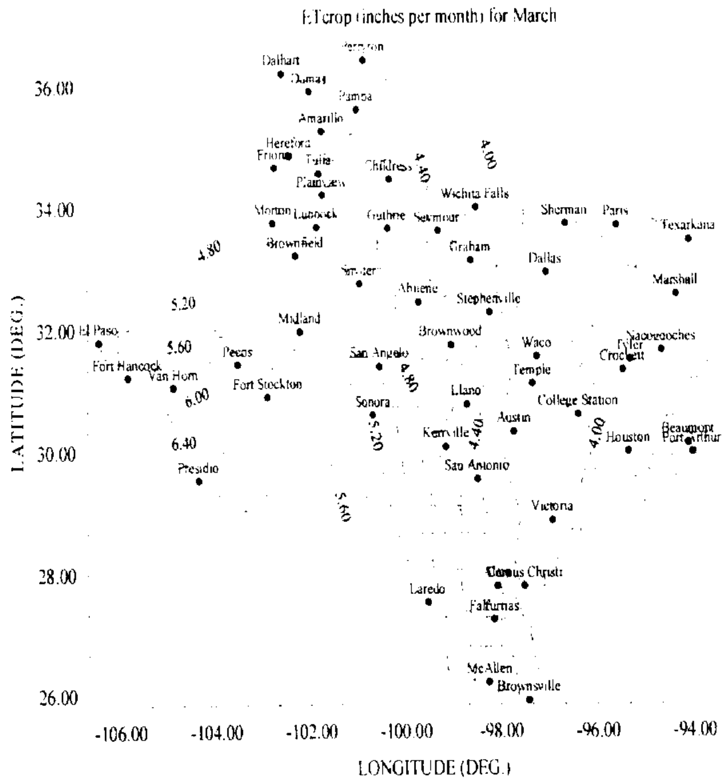


Figure 30.- ET$_{crop}$ for Alfalfa (inches per month).



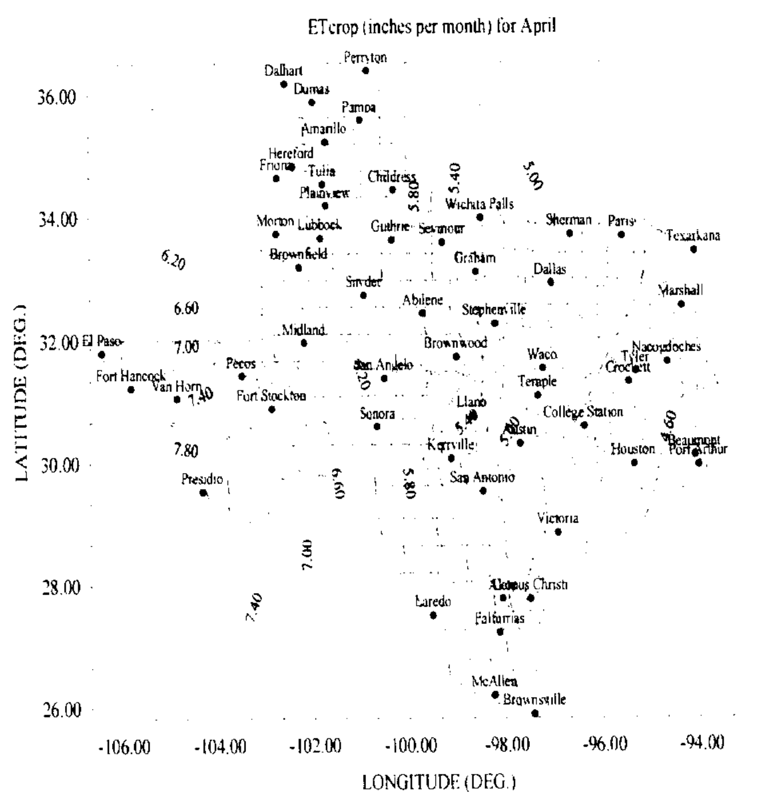
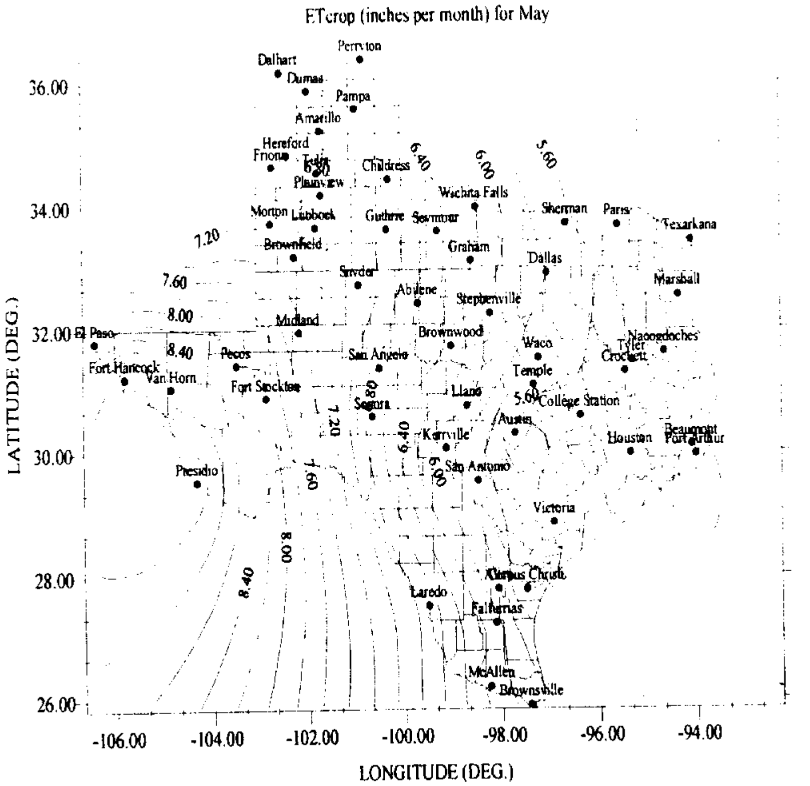


Figure 30.- ET_{crop} ***for Alfalfa (inches per month).***



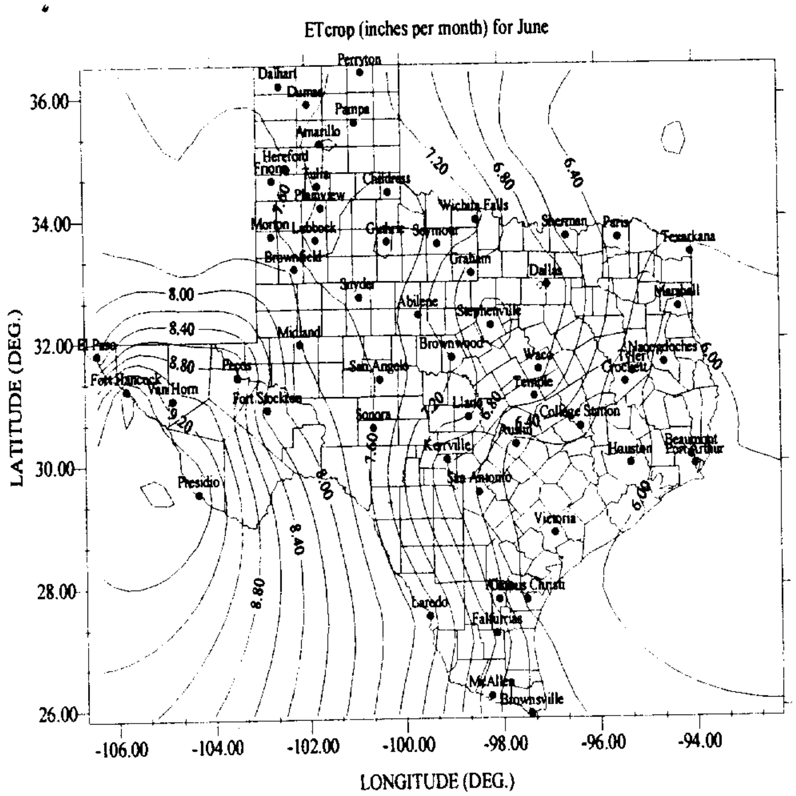


Figure 30.- ET$_{crop}$ for Alfalfa (inches per month).

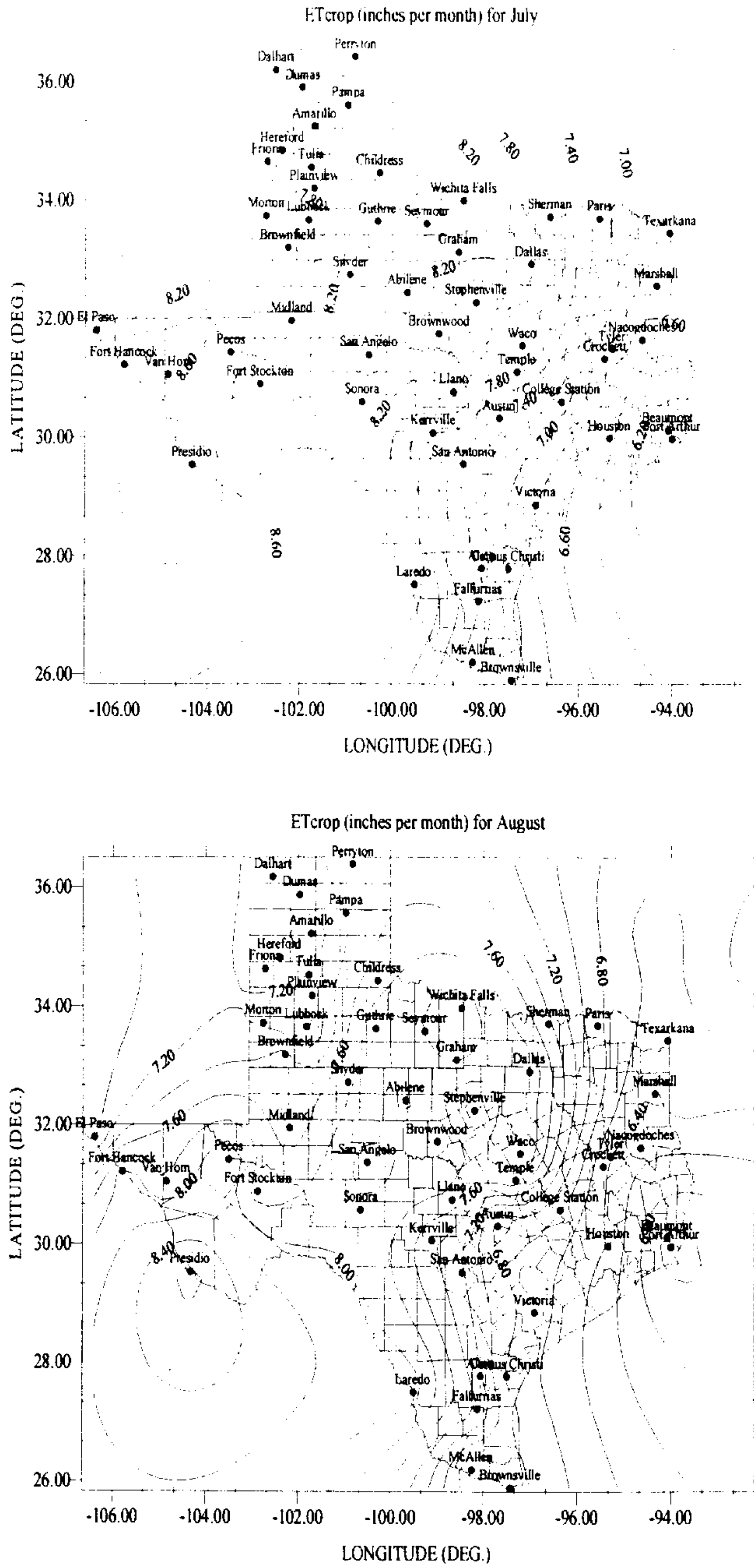
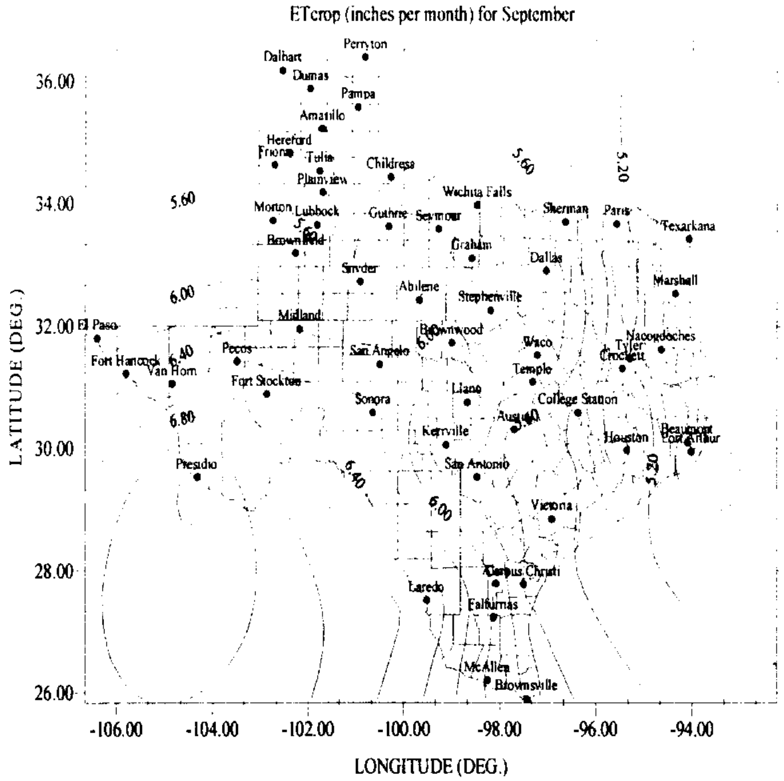


Figure 30.- ET_{crop} for Alfalfa (inches per month).



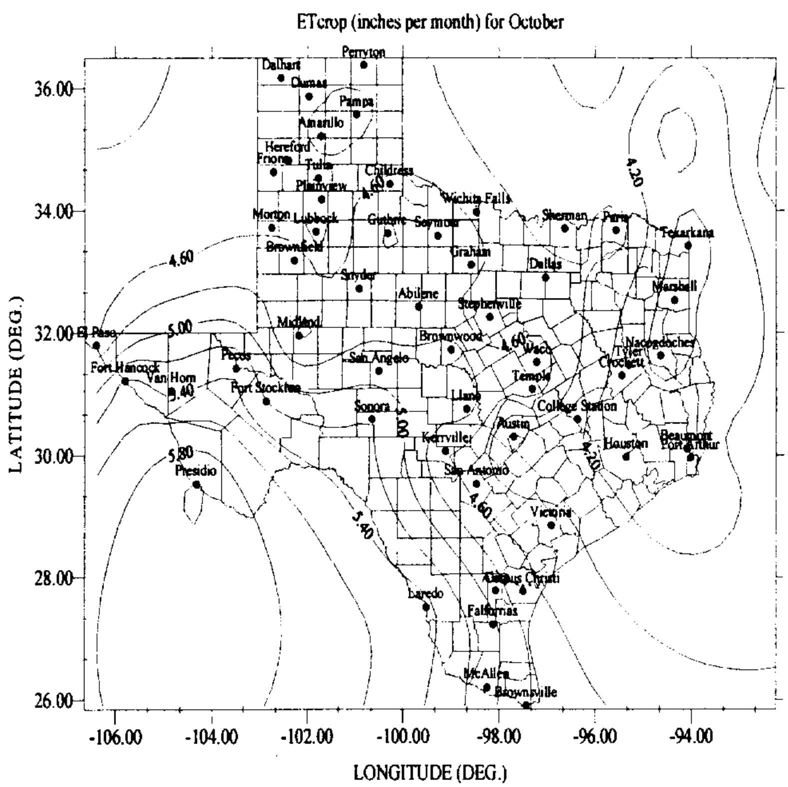


Figure 30.- ET_{crop} for Alfalfa (inches per month).

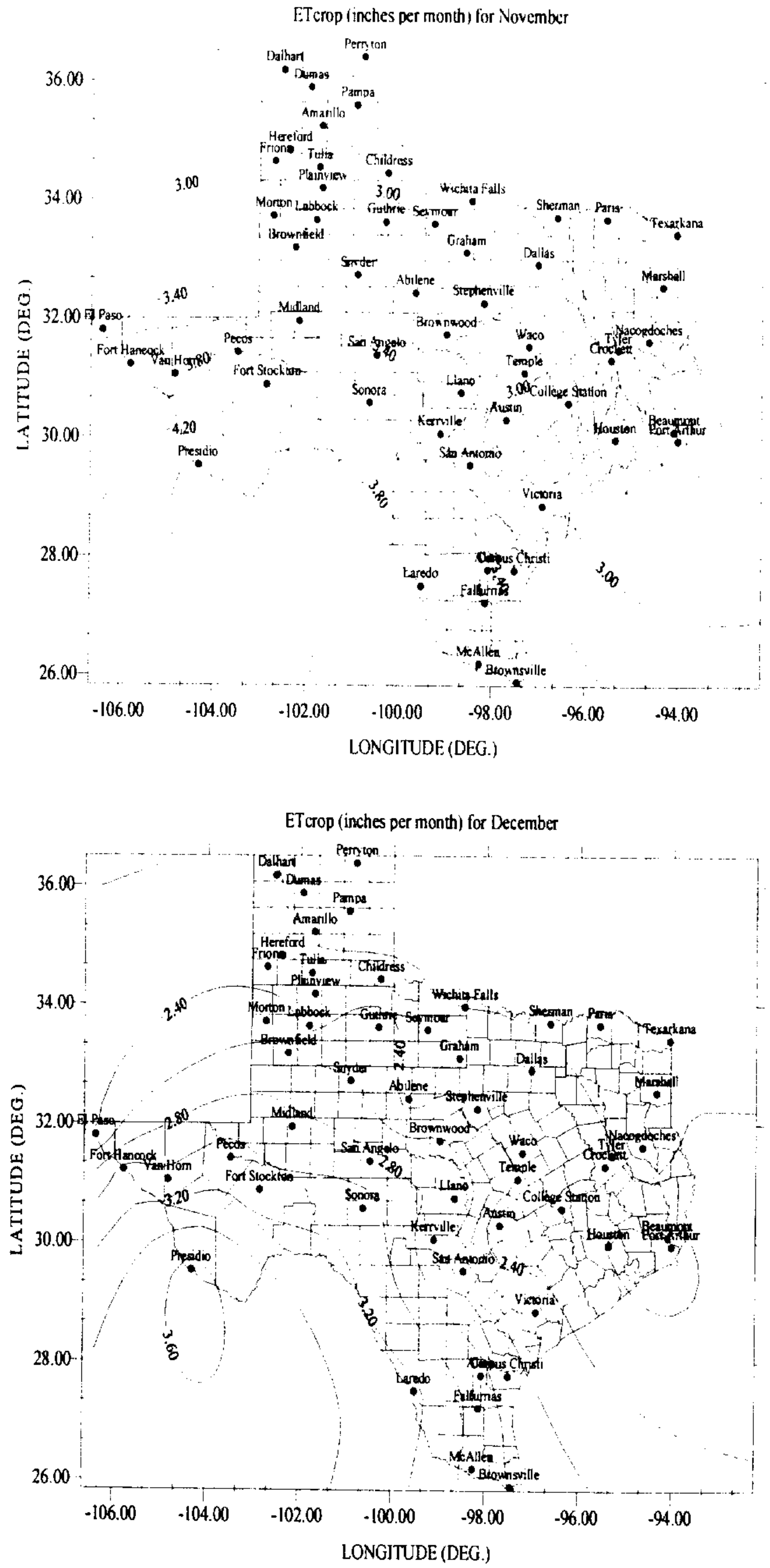


Figure 30.-ET$_{crop}$ for Alfalfa (inches per month).

Example 1

Problem: Mean annual consumptive use, ET_{crop}, is needed for soybeans at Kerrville, TX.

Required Data: Planting date—not available
Length of growing season—not available
Soil texture—clay loam

Solution:

1) Determine planting date and length of growing season. Because it is not given, use general data from Table 13.

Texas crop reporting district is the Edwards Plateau (7).
Planting Date is May 10th.
Length of growing season is 140 days.

2) Determine the dates for the beginning of each growth stage (see Figure 6). Use information in Table 6.

From Table 6: $F_{S1} = 0.15$, $F_{S2} = 0.37$, $F_{S3} = 0.81$ — Growing season within the range given in Table 6.

Start of Canopy Development = Planting Date + F_{S1} × Growing Season
Start of Canopy Development = May 10th + (0.15) × (140) = May 31st

Start of Mid-Season = Planting Date + F_{S2} × Growing Season
Start of Mid-Season = May 10th + (0.37) × (140) = July 1st

Start of Maturation = Planting Date + F_{S3} × Growing Season
Start of Maturation = May 10th + (0.81) × (140) = Aug 31st

Harvest Date = Planting Date + Growing Season
Harvest Date = May 10th + 140 = Sep 27th

3) Select the K_{cp} (peak or maximum value of basal crop coefficient) and K_{cm} (value of basal crop coefficient at crop maturity) values from Table 6.

$K_{cp\text{-}humid} = 1.00$ $K_{cp\text{-}arid} = 1.10$ for moderate wind (< 250 miles/day).

Note: Kerrville is not in the Panhandle of Texas. Therefore, moderate winds should prevail. One can check the wind by consulting wind contours in Appendix B, Figure B2.

4) Adjust K_{cp} and K_{cm} for climate using equations (7) and (8). Determine minimum relative humidity for Appendix B, Figures B1.

Kerrville: Rh_{min} for start of mid-season stage (July 1st) is 44 percent

$K_{cp\_humid} = 1.00$ $K_{cp\_arid} = 1.10$ $K_{cm\_humid} = 0.45$ $K_{cm\_arid} = 0.45$

$$K_{cp} = K_{cp\_humid} + (K_{cp\_arid} - K_{cp\_humid}) \times \left(\frac{70 - Rh_{min}}{50}\right) \quad (7)$$

for $(70 > Rh_{min} > 20)$

$$K_{cp} = 1.00 + (1.10 - 1.00) \times \left(\frac{70 - 44}{50}\right) = 1.05$$

$$K_{cm} = K_{cm\_humid} + (K_{cm\_arid} - K_{cm\_humid}) \times \left(\frac{70 - Rh_{min}}{50}\right) \quad (8)$$

for $(70 > Rh_{min} > 20)$

K_{cm} is the same for climate condition of arid and humid, thus $K_{cm} = 0.45$

5) The K_{cb} values for all annual crops is 0.25 during the "initial" growth stage. With the K_{cb} for the initial stage, the adjusted K_{cp} for the mid-season growth stage(determined above), and the adjusted K_{cm} for the end of the maturation growth stage (determined above), a basal crop coefficient curve can be drawn. Plot the K_{cb} curve with the months on the x-axis and K_{cb} on the y-axis as shown below. The plot is shown in Figure 7.

6) Determine the average K_{cb} value for each month segment. If a month has just a portion of the crop growing season, calculate the average K_{cb} for that portion of the month covered by the crop growing season. The monthly average K_{cb} values are shown on Figure 7.

7) Determine the average number of wet events for each month. Wet events include the expected precipitation events and irrigation events. The average frequency of precipitation events are estimated for various location in Table 14. It is assumed there would be 1 irrigation event for May and 2 irrigation events for the months of May, June, July, and August. No irrigation events were assumed for September.

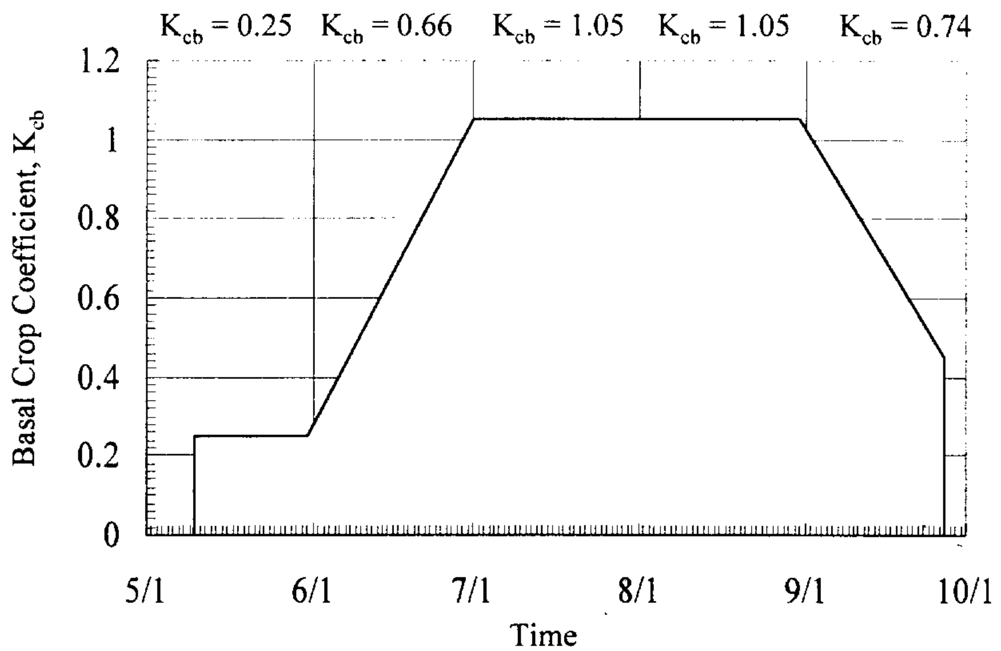


Figure 7.-Basal Crop Coefficient Curve for Example 1.

Month	Wet Events
May	8.08
June	7.85
July	6.23
August	5.62
September	6.15

8) Calculate K_w using Equation 15. The calculations are done below in a table that provides the needed information. F_w, the fraction of the soil surface wetted, is assumed to be 1.0.

Table 3.-Data for Determination of K_w

Month	K_{cb}	Precipitation Frequency	Wetness Factor (WF)	K_w
May * (10 - 31)	0.25**	8.08#	0.63##	0.472+
June	0.66	7.85	0.62	0.211
July	1.05	6.23	0.55	0
August	1.05	5.62	0.51	0
September (1 - 27)	0.74	6.15	0.54	0.140

* Growing season is from May 10th to September 27th.

** Taken from Figure 7.

\# Values obtained from Table 14 for Kerrville plus 1 irrigation in May, 2 irrigation events in June, July, and August, and no irrigation events in September.

\## Values obtained from Table 15.

\+ Calculated using Equation 15. The variable F_w is assumed to be 1.0.

$$K_w = (1 - K_{cb}) \times WF \times F_w \quad \text{for } K_{cb} < 1.0 \qquad (15)$$

and $K_w = 0$ for $K_{cb} \geq 1$.

9) All the information is now available to calculate ET_{crop} for each month. This will be done using Equation 10. The necessary data and the results of the calculations are shown in the following table:

Table 4.-Determination of ET_{crop}

Month	ET_o (inches)	K_{cb}	K_w	Fraction of month in growing season	ET_{crop} (inches)
May * (10 - 31)	6.18**	0.25***	0.472#	22/31=0.71	3.17##
June	6.96	0.66	0.211	1.0	6.06
July	7.96	1.05	0	1.0	8.36
August	7.74	1.05	0	1.0	8.13
September (1 - 27)	6.15	0.74	0.140	27/30=0.90	4.87
Total					30.59

* Growing season is from May 10th to September 27th.
** Values obtained from Figures 14 - 18.
*** Taken from Figure 7.
\# Determined in Table 3.
\#\# Calculated using Equation 10. K_s is assumed to be 1.0.

$$ET_{crop\_mon} = ET_o \times K_{cb} \times K_s + ET_o \times K_w \quad (10)$$

Example 2

Problem: Mean annual consumptive use, ET_{crop}, is needed for grain corn at Pecos, TX.

Required Data: Planting date—not available
Length of growing season—not available
Soil texture—sandy loam

Solution:

1) Determine the planting date and length of growing season. Because it is not given, use general data from Table 13.

Texas crop reporting district is the Trans-Pecos.
Planting date is April 22nd.
Length of growing season is 132 days.

2) Determine the dates for the beginning of each growth stage (see Figure 6). Use information in Table 13.

From Table 6: $F_{S1} = 0.17$ Growing season within the range given in Table 6.
$F_{S2} = 0.45$
$F_{S3} = 0.78$

Start of Canopy Development = Planting Date + F_{S1} × Growing Season
Start of Canopy Development = April 22nd + (0.17) × (132) = May 14th

Start of Mid-Season = Planting Date + F_{S2} × Growing Season
Start of Mid-Season = April 22nd + (0.45) × (132) = June 20th

Start of Maturation = Planting Date + F_{S3} × Growing Season
Start of Maturation = April 22nd + (0.78) × (132) = Aug 3rd

Harvest Date = Planting Date + Growing Season
Harvest Date = April 22nd + 140 = Sep 1st

3) Select the K_{cp} (peak or maximum value of basal crop coefficient) and K_{cm} (value of basal crop coefficient at crop maturity) values from Table 6.

$K_{cp\text{-}humid} = 1.05$ $K_{cp\text{-}arid} = 1.15$ for moderate wind (< 250 miles/day).
$K_{cm\_humid} = 0.55$ $K_{cm\text{-}arid} = 0.60$

Note: Pecos is not in the Panhandle of Texas. Therefore, moderate winds should prevail. One can check the wind by consulting wind contours in Appendix B, Figure B2.

4) Adjust K_{cp} and K_{cm} for climate using Equations 7 and 8. Determine minimum relative humidity for Appendix B, Figures B1.

Kerrville: Rh_{min} for start of mid-season stage (July 1st) is 31 percent
Rh_{min} for end of maturation stage (September 1st) is 39 percent.

$K_{cp\_humid} = 1.05$ $K_{cp\_arid} = 1.15$ $K_{cm\_humid} = 0.55$ $K_{cm\_arid} = 0.60$

$$K_{cp} = K_{cp\_humid} + \left(K_{cp\_arid} - K_{cp\_humid}\right)\times\left(\frac{70 - Rh_{min}}{50}\right) \quad (7)$$

for $(70 > Rh_{min} > 20)$

$$K_{cp} = 1.05 + (1.15 - 1.05)\times\left(\frac{70-31}{50}\right) = 1.13$$

$$K_{cm} = K_{cm\_humid} + \left(K_{cm\_arid} - K_{cm\_humid}\right)\times\left(\frac{70 - Rh_{min}}{50}\right) \quad (8)$$

for $(70 > Rh_{min} > 20)$

$$K_{cm} = 0.55 + \left(0.60 - 0.55\right)\times\left(\frac{70-39}{50}\right) = 0.58$$

5) The K_{cb} values for all annual crops are 0.25 during the "initial" growth stage. With the K_{cb} for the initial stage, the adjusted K_{cp} for the mid-season growth stage (determined above), and the adjusted K_{cm} for the end of the maturation growth stage (determined above), a basal crop coefficient curve can be drawn. Plot the K_{cb} curve with the months on the x-axis and K_{cb} on the y-axis as shown below. The plot is shown in Figure 31.

6) Determine the average K_{cb} value for each month segment. If a month has just a portion of the crop growing season, calculate the average K_{cb} for that portion of the month covered by the crop growing season. The monthly average K_{cb} values are shown on Figure 31.

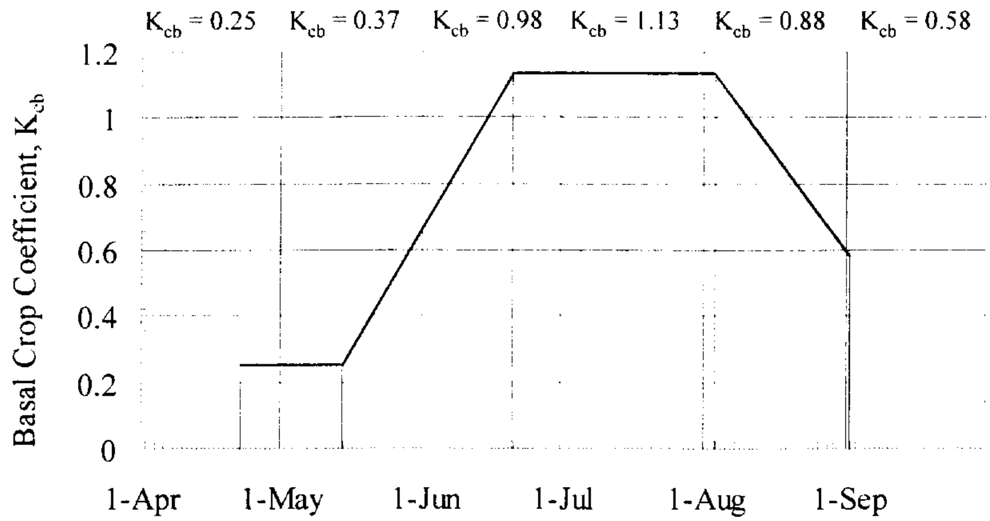
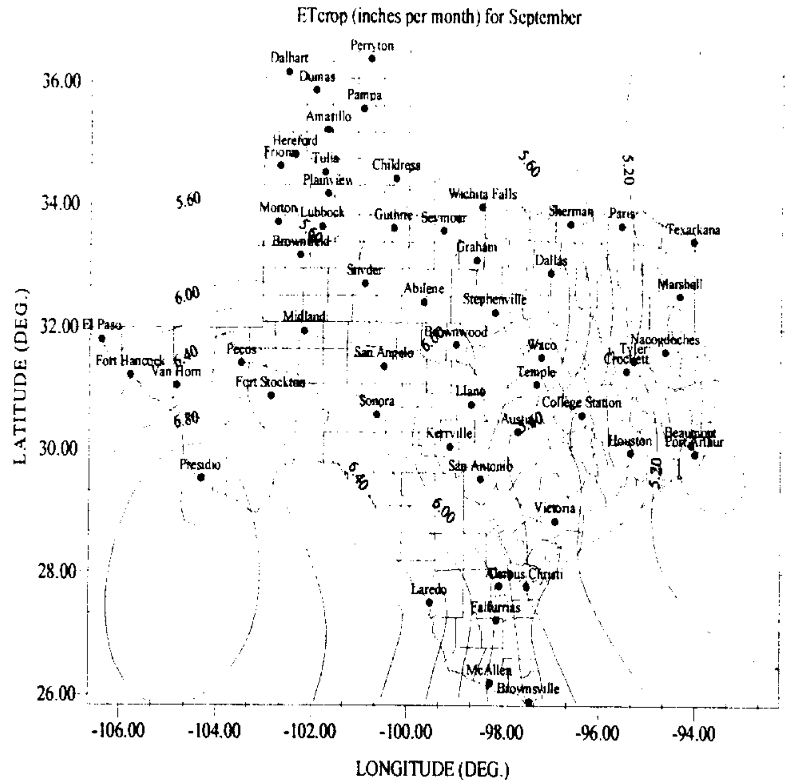


Figure 31.-Basal Crop Coefficient Curve for Example 2.



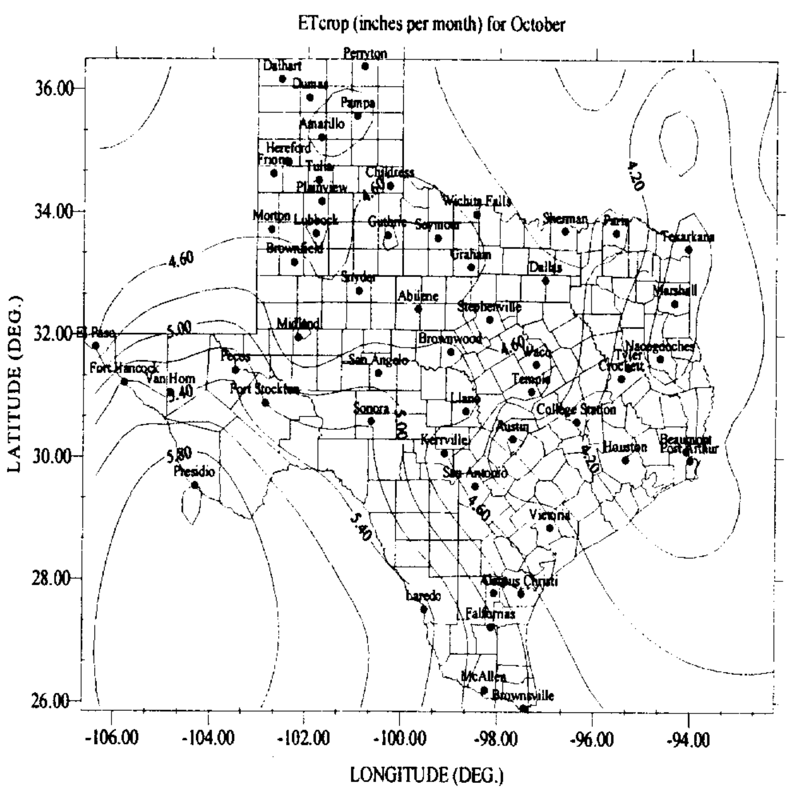


Figure 30.- ET$_{crop}$ for Alfalfa (inches per month).

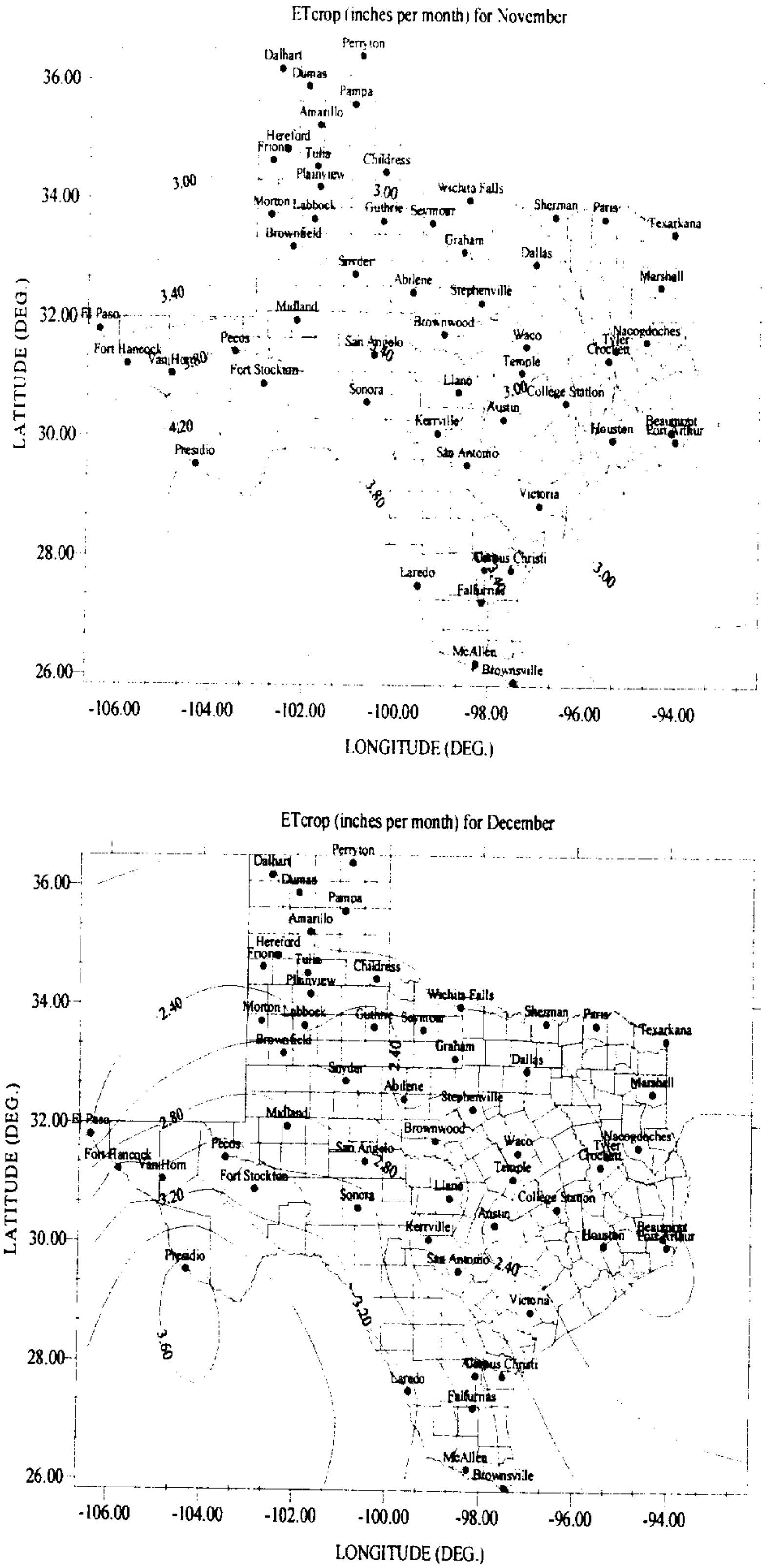


Figure 30.-ET$_{crop}$ for Alfalfa (inches per month).

Example 1

Problem: Mean annual consumptive use, ET_{crop}, is needed for soybeans at Kerrville, TX.

Required Data: Planting date—not available
Length of growing season—not available
Soil texture—clay loam

Solution:

1) Determine planting date and length of growing season. Because it is not given, use general data from Table 13.

Texas crop reporting district is the Edwards Plateau (7).
Planting Date is May 10th.
Length of growing season is 140 days.

2) Determine the dates for the beginning of each growth stage (see Figure 6). Use information in Table 6.

From Table 6: $F_{S1} = 0.15$ Growing season within the range given in Table 6.
$F_{S2} = 0.37$
$F_{S3} = 0.81$

Start of Canopy Development = Planting Date + F_{S1} × Growing Season
Start of Canopy Development = May 10th + (0.15) × (140) = May 31st

Start of Mid-Season = Planting Date + F_{S2} × Growing Season
Start of Mid-Season = May 10th + (0.37) × (140) = July 1st

Start of Maturation = Planting Date + F_{S3} × Growing Season
Start of Maturation = May 10th + (0.81) × (140) = Aug 31st

Harvest Date = Planting Date + Growing Season
Harvest Date = May 10th + 140 = Sep 27th

3) Select the K_{cp} (peak or maximum value of basal crop coefficient) and K_{cm} (value of basal crop coefficient at crop maturity) values from Table 6.

$K_{cp\text{-}humid} = 1.00$ $K_{cp\text{-}arid} = 1.10$ for moderate wind (< 250 miles/day).

Note: Kerrville is not in the Panhandle of Texas. Therefore, moderate winds should prevail. One can check the wind by consulting wind contours in Appendix B, Figure B2.

4) Adjust K_{cp} and K_{cm} for climate using equations (7) and (8). Determine minimum relative humidity for Appendix B, Figures B1.

Kerrville: Rh_{min} for start of mid-season stage (July 1st) is 44 percent

$K_{cp\_humid} = 1.00$ $K_{cp\_arid} = 1.10$ $K_{cm\_humid} = 0.45$ $K_{cm\_arid} = 0.45$

$$K_{cp} = K_{cp\_humid} + \left(K_{cp\_arid} - K_{cp\_humid}\right) \times \left(\frac{70 - Rh_{min}}{50}\right) \tag{7}$$

for $(70 > Rh_{min} > 20)$

$$K_{cp} = 1.00 + (1.10 - 1.00) \times \left(\frac{70 - 44}{50}\right) = 1.05$$

$$K_{cm} = K_{cm\_humid} + \left(K_{cm\_arid} - K_{cm\_humid}\right) \times \left(\frac{70 - Rh_{min}}{50}\right) \tag{8}$$

for $(70 > Rh_{min} > 20)$

K_{cm} is the same for climate condition of arid and humid, thus $K_{cm} = 0.45$

5) The K_{cb} values for all annual crops is 0.25 during the "initial" growth stage. With the K_{cb} for the initial stage, the adjusted K_{cp} for the mid-season growth stage(determined above), and the adjusted K_{cm} for the end of the maturation growth stage (determined above), a basal crop coefficient curve can be drawn. Plot the K_{cb} curve with the months on the x-axis and K_{cb} on the y-axis as shown below. The plot is shown in Figure 7.

6) Determine the average K_{cb} value for each month segment. If a month has just a portion of the crop growing season, calculate the average K_{cb} for that portion of the month covered by the crop growing season. The monthly average K_{cb} values are shown on Figure 7.

7) Determine the average number of wet events for each month. Wet events include the expected precipitation events and irrigation events. The average frequency of precipitation events are estimated for various location in Table 14. It is assumed there would be 1 irrigation event for May and 2 irrigation events for the months of May, June, July, and August. No irrigation events were assumed for September.

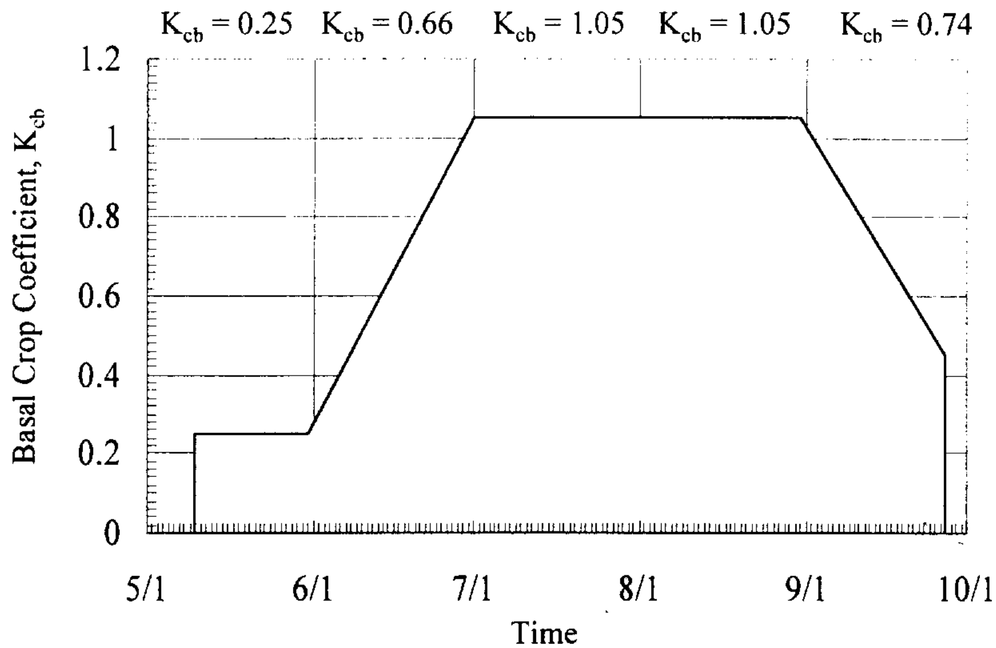


Figure 7.-Basal Crop Coefficient Curve for Example 1.

Month	Wet Events
May	8.08
June	7.85
July	6.23
August	5.62
September	6.15

8) Calculate K_w using Equation 15. The calculations are done below in a table that provides the needed information. F_w, the fraction of the soil surface wetted, is assumed to be 1.0.

Table 3.-Data for Determination of K_w

Month	K_{cb}	Precipitation Frequency	Wetness Factor (WF)	K_w
May * (10 - 31)	0.25**	8.08#	0.63##	0.472+
June	0.66	7.85	0.62	0.211
July	1.05	6.23	0.55	0
August	1.05	5.62	0.51	0
September (1 - 27)	0.74	6.15	0.54	0.140

* Growing season is from May 10th to September 27th.

** Taken from Figure 7.

\# Values obtained from Table 14 for Kerrville plus 1 irrigation in May, 2 irrigation events in June, July, and August, and no irrigation events in September.

\#\# Values obtained from Table 15.

\+ Calculated using Equation 15. The variable F_w is assumed to be 1.0.

$$K_w = (1 - K_{cb}) \times WF \times F_w \quad \text{for } K_{cb} < 1.0 \qquad (15)$$

and $K_w = 0$ for $K_{cb} \geq 1$.

9) All the information is now available to calculate ET_{crop} for each month. This will be done using Equation 10. The necessary data and the results of the calculations are shown in the following table:

Table 4.-Determination of ET_{crop}

Month	ET_o (inches)	K_{cb}	K_w	Fraction of month in growing season	ET_{crop} (inches)
May * (10 - 31)	6.18**	0.25***	0.472#	22/31=0.71	3.17##
June	6.96	0.66	0.211	1.0	6.06
July	7.96	1.05	0	1.0	8.36
August	7.74	1.05	0	1.0	8.13
September (1 - 27)	6.15	0.74	0.140	27/30=0.90	4.87
Total					30.59

* Growing season is from May 10th to September 27th.

** Values obtained from Figures 14 - 18.

*** Taken from Figure 7.

\# Determined in Table 3.

\## Calculated using Equation 10. K_s is assumed to be 1.0.

$$ET_{crop\_mon} = ET_o \times K_{cb} \times K_s + ET_o \times K_w \tag{10}$$

Example 2

Problem: Mean annual consumptive use, ET_{crop}, is needed for grain corn at Pecos, TX.

Required Data: Planting date—not available
Length of growing season—not available
Soil texture—sandy loam

Solution:

1) Determine the planting date and length of growing season. Because it is not given, use general data from Table 13.

Texas crop reporting district is the Trans-Pecos.
Planting date is April 22nd.
Length of growing season is 132 days.

2) Determine the dates for the beginning of each growth stage (see Figure 6). Use information in Table 13.

From Table 6: $F_{S1} = 0.17$, $F_{S2} = 0.45$, $F_{S3} = 0.78$ — Growing season within the range given in Table 6.

Start of Canopy Development = Planting Date + F_{S1} × Growing Season
Start of Canopy Development = April 22nd + (0.17) × (132) = May 14th

Start of Mid-Season = Planting Date + F_{S2} × Growing Season
Start of Mid-Season = April 22nd + (0.45) × (132) = June 20th

Start of Maturation = Planting Date + F_{S3} × Growing Season
Start of Maturation = April 22nd + (0.78) × (132) = Aug 3rd

Harvest Date = Planting Date + Growing Season
Harvest Date = April 22nd + 140 = Sep 1st

3) Select the K_{cp} (peak or maximum value of basal crop coefficient) and K_{cm} (value of basal crop coefficient at crop maturity) values from Table 6.

$K_{cp\text{-}humid} = 1.05$ $K_{cp\text{-}arid} = 1.15$ for moderate wind (< 250 miles/day).
$K_{cm\_humid} = 0.55$ $K_{cm\text{-}arid} = 0.60$

Note: Pecos is not in the Panhandle of Texas. Therefore, moderate winds should prevail. One can check the wind by consulting wind contours in Appendix B, Figure B2.

4) Adjust K_{cp} and K_{cm} for climate using Equations 7 and 8. Determine minimum relative humidity for Appendix B, Figures B1.

Kerrville: Rh_{min} for start of mid-season stage (July 1st) is 31 percent
Rh_{min} for end of maturation stage (September 1st) is 39 percent.

$K_{cp\_humid} = 1.05$ $K_{cp\_arid} = 1.15$ $K_{cm\_humid} = 0.55$ $K_{cm\_arid} = 0.60$

$$K_{cp} = K_{cp\_humid} + \left(K_{cp\_arid} - K_{cp\_humid}\right) \times \left(\frac{70 - Rh_{min}}{50}\right) \quad (7)$$

for $(70 > Rh_{min} > 20)$

$$K_{cp} = 1.05 + (1.15 - 1.05) \times \left(\frac{70 - 31}{50}\right) = 1.13$$

$$K_{cm} = K_{cm\_humid} + \left(K_{cm\_arid} - K_{cm\_humid}\right) \times \left(\frac{70 - Rh_{min}}{50}\right) \quad (8)$$

for $(70 > Rh_{min} > 20)$

$$K_{cm} = 0.55 + \left(0.60 - 0.55\right) \times \left(\frac{70 - 39}{50}\right) = 0.58$$

5) The K_{cb} values for all annual crops are 0.25 during the "initial" growth stage. With the K_{cb} for the initial stage, the adjusted K_{cp} for the mid-season growth stage (determined above), and the adjusted K_{cm} for the end of the maturation growth stage (determined above), a basal crop coefficient curve can be drawn. Plot the K_{cb} curve with the months on the x-axis and K_{cb} on the y-axis as shown below. The plot is shown in Figure 31.

6) Determine the average K_{cb} value for each month segment. If a month has just a portion of the crop growing season, calculate the average K_{cb} for that portion of the month covered by the crop growing season. The monthly average K_{cb} values are shown on Figure 31.

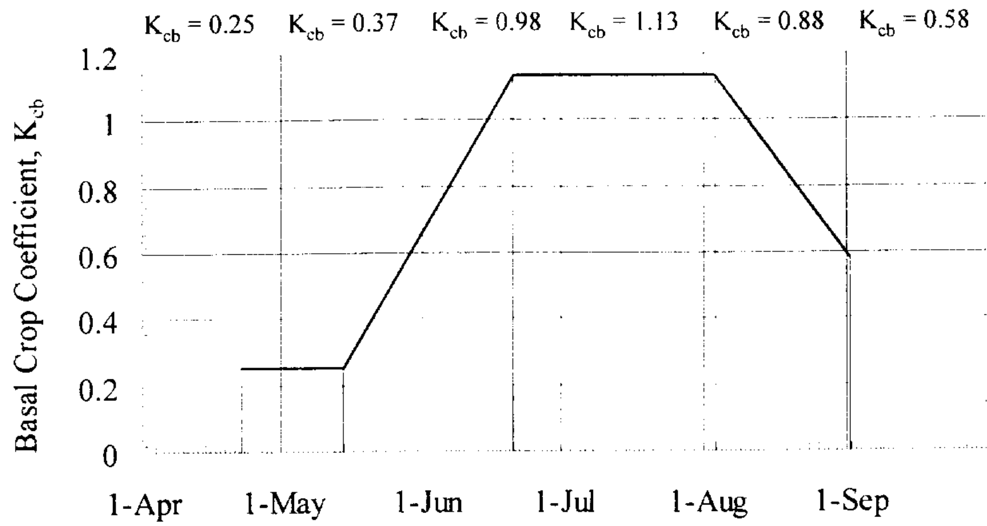


Figure 31.-Basal Crop Coefficient Curve for Example 2.

7) Determine the average number of wet events for each month. Wet events include the expected precipitation events and irrigation evenst. The average frequency of precipitation events are estimated for various locations in Table 14. It is assumed there would be 1 irrigation event for April, 3 irrigation events May, 6 irrigation events for the months of June and July, 1 irrigation event for August, and no irrigation events for September.

Month	Wet Events
April	2.55
May	6.28
June	9.03
July	9.38
August	4.86
September	4.97

8) Calculate K_w using Equation 15. The calculation are done below in a table which provides the needed information. F_w, the fraction of the soil surface wetted, is assumed to be 1.0.

Table 17.-Data for Determination of K_w

Month	K_{cb}	Precipitation Frequency	Wetness Factor (WF)	K_w
April * (22-30)	0.25**	2.55#	0.16##	0.120+
May	0.37	6.28	0.40	0.252
June	0.98	9.03	0.55	0.011
July	1.13	9.38	0.57	0
August	0.88	4.86	0.31	0.037
September (1 day)	0.58	4.97	0.32	0.134

* Growing season is from April 22nd to September 1st.

** Taken from Figure 7.

\# Values obtained from Table 14 for Pecos plus the assumed irrigation events.

\## Values obtained from Table 15.

\+ Calculated using Equation 15. The variable F_w is assumed to be 1.0.

$$K_w = (1 - K_{cb}) \times WF \times F_w \quad \text{for } K_{cb} < 1.0 \tag{15}$$

and $K_w = 0$ for $K_{cb} \geq 1$.

9) All the information is now available to calculate ET_{crop} for each month. This will be done using Equation 10. The necessary data and the results of the calculations are shown in the following table:

Table 18.-Determination of ET_{crop}

Month	ET_o (inches)	K_{cb}	K_w	Fraction of month in growing season	ET_{crop} (inches)
April * (22 - 30)	7.74**	0.25***	0.120#	9/30=0.30	0.86##
May	8.92	0.37	0.252	1.0	5.55
June	9.29	0.98	0.011	1.0	9.21
July	9.37	1.13	0	1.0	10.59
August	8.63	0.88	0.037	1.0	7.91
September (1 day)	7.10	0.58	0.134	1/30=0.033	0.17
Total					34.29

* Growing season is from April 22nd to September 1st.
** Values obtained from Figures 13 - 18.
*** Taken from Figure 31.
# Determined in Table 17.
Calculated using Equation 10. K_s is assumed to be 1.0.

$$ET_{crop\_mon} = ET_o \times K_{cb} \times K_s + ET_o \times K_w \quad (10)$$

Mean Crop Consumptive Use.....

Sample Calculation for SCS (1993) Penman-Monteith Procedure

Enter Date of This Run: *December 27, 1995*

User's Name: John Borrelli

The following method of calculating evapotranspiration is based on the Penman-Monteith equation. Calculation procedures were adapted from the SCS publicaton "Chapter 2--Irrigation Water Requirements," Part 623 of the National Engineering Handbook, United States Department of Agriculture, Soil Conservation Service. NEH-623-2. P.O. Box 2890, Washington, D.C. 20013. September, 1993.

The SCS publication states the following:

"Jensen, et al. (1990) compared 20 methods of computing ET_o for arid and humid locations. They found that the Penman-Monteith method as modified by Allen (1986) was the most accurate for either environment. Because of its accuracy, the Penman-Monteith method is recommended when air temperature, relative humidity, wind speed, and solar radiation data are available or can be reliably estimated. The method can also be adjusted to the physical features of the local weather station."

Penman-Monteith Equation

$$ETo = \left(\frac{1}{\lambda}\right)\cdot\left[\left(\frac{\Delta}{\Delta+\gamma s}\right)\cdot(Rn - G) + \left(\frac{\gamma}{\Delta+\gamma s}\right)\cdot\left(\frac{0.622\cdot K1\cdot\lambda\cdot\rho}{BP}\right)\cdot\frac{(eoz - ed)}{ra}\right]$$

List of Variables

α = albedo of crop and soil surface

Δ = slope of vapor pressure curve (mb/deg F)

ε = net atmospheric emittance

γ = psychrometric constant (mb/deg F)

λ = heat of vaporization of water (lang/in)

σ = Stephan Boltzman constant

Θd = solar declination angle (degrees)

Θm = solar altitude at solar noon (degrees)

ys = adjusted psychrometric constant (mb/deg F)
a = emperical slope in longwave radiation equation
a1 = factor to account for the change of emissivity because of day length
b = emperical intercept for longwave radiation equation

cp = specific heat of dry air (lang/in/deg F)

ed = saturated vapor pressure at the dew point temperature (mb)

eo = saturation vapor pressure (mb)

eoz = average saturated vapor pressure for the day (mb)

eozmax = saturated vapor pressure at the maximum temperature (mb)
eozmin = saturated vapor pressure at the minimum temperature (mb)
hc = crop height (in)

nN = ratio of actual to maximum possible sunshine hours (nN = n/N)
rc = surface resistance to vapor transport (d/mi)

ra = aerodynamic resistance to sensible heat and vapor transfer (d/mi)

A = leading parameter of clear sky radiation equation

B = cosine eoefficient in clear sky radiation equation

BP = barometric pressure (mb)
DOY = the day of the year
Elev = elevation above sea level (ft)

ET_o *= the evapotranspiration rate for a grass reference crop (in/d)*

G = soil heat flux (lang/d)

Lat = latitude (degrees)

Rb = net outgoing longwave radiation (lang/d)
Rbo = the net outgoing longwave solar radiation on a clear day (lang/d)
Reso = clear sky radiation correction term for elevation (lang/d)
Rn = net radiation (lang/d)

Roso = clear sky radiation at sea level (lang/d)
Rs = incoming solar radiation (lang/d)
Rso = the amount of incident solar radiation on a clear day (lang/d)
Ta = mean air temperature (deg F)

Tmax = maximum air temperature for the day (deg F)

Tmin = minimum air temperature for the day (deg F)

Ts4 = effective absolute temperature of the earth's surface raised to the fourth power (deg K)

Uf = adjustment factor for wind speed that correct for vegetation at weather station

Uz = wind run at height Zw (miles/day)

Zp = height of air temperature measurement (ft)

Zw = height of wind speed measurement (ft)

Start of Calculations

****

Input the Values for the Variables Below:

Tmin := 66	*Minimum Air Temperature (deg F)*
Tmax := 94	*Maximum Air Temperature (deg F)*
Tp := 82	*Mean Air Temperature for the Preceding Three Days (deg F)*
Tdp := 62	*Dew Point Temperature (deg F)*
Elev := 3000	*Elevation of Station (ft)*
Zw := 6.6	*Height of Anomometer Above the Soil Surface (ft)*
Zp := 4.9	*Height of the Temperature and Humidty Probe (ft)*
Uz := 350	*Measured Wind Speed at Height Zw (mi/d)*
hw := 5	*Height of the crop at the weather station (in)*
hc := 5	*Height of Crop (in)*
Ur := 2	*Ratio of daytime to nighttime wind speeds*
DOY := 201	*Day of Year (1 - 365)*
Lat := 40	*Latitude (deg)*
nN := 0.825	*Ratio of Actual to Maximum Possible Sunshine Hours*
Rs := 695	*Actual incoming solar radiation (lang/d)*

$Ra := 976$ *Extraterrestral solar radiation at top of atmos (lang/d)*

****

$$Ta := \frac{Tmin + Tmax}{2}$$

$Ta = 80$ *Mean Air Temperature (deg F)*

$\lambda := 1543 - 0.796 \cdot Ta$

$\lambda = 1.479 \cdot 10^3$ *Heat of Vaporization of Water (lang/in)*

$$BP := 1013 \cdot \left(1 - \frac{Elev}{145350}\right)^{5.26}$$

$BP = 907.751$ *Barometric Pressure (mb)*

$cp := 0.339$ *Specific Heat of Dry Air (lang/in/deg F)*

$$\gamma := \frac{cp \cdot BP}{0.622 \cdot \lambda}$$

$\gamma = 0.334$ *Psychrometric Constant (mb/deg F)*

$$ed := \left(\frac{164.8 + Tdp}{157}\right)^8$$

$ed = 18.965$ *Saturated Vapor Pressure at the Dew Point Tempaerature (mb)*

$$eozmax := \left(\frac{164.8 + Tmax}{157}\right)^8$$

Saturated Vapor Pressure at the Maximum Temperature (mb)

$eozmax = 54.515$

$$eozmin := \left(\frac{164.8 + Tmin}{157}\right)^8$$

Saturated Vapor Pressure at the Minimum Temperature (mb)

$eozmin = 21.812$

$$eoz := \frac{eozmax + eozmin}{2}$$

$eoz = 38.163$ *Average Saturated Vapor Pressure for the day (mb)*

$$Uf := \frac{\ln\left[97.56 \cdot \left(\frac{Zw}{hc}\right) - 5.42\right]}{\ln\left[97.56 \cdot \left(\frac{Zw}{hw}\right) - 5.42\right]}$$

$Uf = 1$ *Adjustment Factor for Wind Speed*

$Uz := Uf \cdot Uz$ *Adjusted wind run at height Zw (miles/day)*

$A := 753.6 - 6.53 \cdot Lat + 0.0057 \cdot Elev$

$A = 509.5$ *Leading Parameter of Clear Sky Radiation Equation*

$B := -7.1 + 6.40 \cdot Lat + Elev \cdot 0.0030$

$B = 257.9$ *Cosine Coefficient in Clear Sky Radiation Equation*

$$Rso := A + B \cdot \cos\left[(0.9863 \cdot (DOY - 170)) \cdot \frac{\pi}{180}\right]$$

$Rso = 731.542$ *Amount of Incident Solar Radiation on aClear Day (lang/d)*

$a1 := 0.26 + 0.1 \cdot \exp\left[-(0.0154 \cdot (DOY - 176))^2\right]$ *Factor to Account for Effect of Day Length on Emissivity*

$a1 = 0.346$

$\varepsilon := a1 - 0.044 \cdot ed^{0.5}$

$\varepsilon = 0.155$ *Atmospheric Emittance*

$$Ts4 := 0.5 \cdot \left[\left(\frac{5}{9} \cdot Tmax + 255.4\right)^4 + \left(\frac{5}{9} \cdot Tmin + 255.4\right)^4\right]$$

$Ts4 = 8.116 \cdot 10^9$ *Effective Temperature of Earth Surface Taken to the 4th Power*

$\sigma := 11.71 \cdot 10^{-8}$ *Stephan-Boltzman Constant*

$Rbo := \varepsilon \cdot \sigma \cdot Ts4$

$Rbo = 146.936$ *Net Outgoing Longwave Radiation on a Clear Day (lang/d)*

$$jb1 := \frac{Rs}{Rso}$$

$jb1 = 0.95$

$a := if(jb1 > 0.7, 1.126, 1.017)$

$a = 1.126$ *Emperical Slopein Longwave Radiation Equation*

$b := if(jb1 > 0.7, -0.07, -0.06)$

$b = -0.07$ *Empirical Intercept for Longwave Radiation Equation*

$$Rb := \left(a \cdot \frac{Rs}{Rso} + b\right) \cdot Rbo$$

$Rb = 146.9$ *Net Outgoing Longwave Radiation (lang/d)*

$$\theta d := \operatorname{asin}\left[\left[0.39795\cdot\cos\left[(0.98563\cdot(DOY - 173))\cdot\frac{\pi}{180}\right]\right]\right]\cdot\frac{180}{\pi}$$

$\theta d = 20.651$ *Solar Declinitation Angle (deg)*

$$\theta m := \operatorname{asin}\left(\sin\left(\theta d\cdot\frac{\pi}{180}\right)\cdot\sin\left(Lat\cdot\frac{\pi}{180}\right) + \cos\left(\theta d\cdot\frac{\pi}{180}\right)\cdot\cos\left(Lat\cdot\frac{\pi}{180}\right)\right)\cdot\frac{180}{\pi}$$

$\theta m = 70.651$ *Solar Altitude at Solar Noon (deg)*

$$\alpha := 0.108 + 0.000939\cdot\theta m + 0.257\cdot\exp\left[-\frac{\theta m}{\frac{180}{\pi}}\right]$$

$\alpha = 0.249$ *Albedo of Crop and Soil Surface*

$Rn := (1 - \alpha)\cdot Rs - Rb$

$Rn = 374.886$ *Net Radiation (lang/d)*

$LAI := 0.61\cdot hc$ *Leaf area index*

$$rc := \frac{1.863}{0.5\cdot LAI}$$

$rc = 1.222$ *Surface Resistance to Vapor Transport (d/mi)*

$$ra := \frac{\ln\left(97.56\cdot\frac{Zw}{hc} - 5.42\right)\cdot\ln\left(975.6\cdot\frac{Zp}{hc} - 54.2\right)}{0.168\cdot Uz}$$

$ra = 0.557$ *Aerodynamic Resistance to Sensible Heat and Vapor Transfer (d/mi)*

$\gamma = 0.334$

$$\gamma s := \gamma\cdot\left(1 + \frac{rc}{ra}\right)$$

$\gamma s = 1.068$ *Adjusted Psychrometric Constant (mb/deg F)*

$$\Delta := 0.051\cdot\left(\frac{164.8 + Ta}{157}\right)^7$$

$\Delta = 1.143$ *Slope of the Saturated Vapor Pressure Curve (mb/deg F)*

$cs := 5$ *Empirical Specific Heat Coefficient for Soil (lang/deg F/d)*

$G := cs\cdot(Ta - Tp)$

$G = -10$ *Soil Heat Flux (lang/d)*

$EQ241 := 82 - 0.186\cdot Ta$

EQ241 = 67.12 *A term equal to (0.622)(K_1)(λ)(ρ)/(BP) or Equation 2-41*

$$ETo := \frac{1}{\lambda}\cdot\left[\frac{\Delta}{\Delta+\gamma s}\cdot(Rn-G)+\frac{\gamma}{\gamma s+\Delta}\cdot(EQ241)\cdot\frac{eoz-ed}{ra}\right]$$

ETo = 0.371 *The Evapotranspiration Rate for a Grass Reference Crop (in/d)*

<u>Data used in this example is the same as used for Example 2-11 in SCS (1993).</u>

Chapter 4

Turfgrass

Turfgrass makes up the largest acreage of any irrigated crop in Texas—approximately 3,000,000 acres (Gerst et al., 1982). Furthermore, turfgrass is the major component of urban landscapes. However, a review of the consumptive use studies reported by Jensen et al. (1990) reveals very few studies related to turfgrass. In recent years, several studies comparing the consumptive use of various grass species and varieties within species have been completed. Most of these studies have not provided the K_{cb} values desired for the estimation of evapotranspiration by the Penman-Monteith procedure. Furthermore, there are numerous comparisons with various reference crop evapotranspiration equations making it difficult to use many of the reported K_c or K_{cb} values. To provide comparative values, the ET rates of the various grasses were compared to perennial rye grass to establish the relative K_{cb} values. It should be noted that Feldhake et al. (1983) stated that a large degree of heterogeneity exists in residential (as well as in parks and cemeteries) turf management practices.

Cool-Season Grasses

Recent research by Aronson et al. (1987), Feldhake et al. (1983), Kim and Beard (1988), Kopec et al. (1988), Kopec et al. (1990), Garrot and Mancino (1994), Carrow (1995), and Qian et al. (1996) has provided a body of data that allows one to estimate, with some confidence, the K_{cb} values for most common turfgrasses. It is somewhat fortuitous that grass crop reference evapotranspiration, ET_o, was developed for a cool-season turfgrass—rye grass. Remember ET_o is defined as the rate of evapotranspiration from an extensive surface of 3 to 6 inches tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water.

K_{cb} for Rye Grass

Because the grass reference was established primarily using data from the rye grass lysimeters at Davis, California, one can conclude that the K_{cb} value for rye grass is 1.0 when the average height of grass is kept at 5 inches. With this established, K_{cb} values for other grasses can be inferred from the several comparative studies mentioned above.

Aronson et al. (1987) found Kentucky bluegrass and rye grass to have essentially the same evapotranspiration rates. Tall fescue also appears to have the same evapotranspiration as rye grass according to the experiments conducted by Borrelli et al. (1979). Feldhake et al. (1983) found that the ET from tall fescue was 1.02 times the ET for Kentucky bluegrass or, for all practical purposes, tall fescue has the same ET rates as Kentucky bluegrass. All these grasses are cool-season grasses (C3 metabolism) and are expected to have the same evapotranspiration rates if mowing height and other management factors are the same. Thus a K_{cb} of 1.0 would be appropriate for rye grass, Kentucky bluegrass, and tall fescue grass when well watered, actively growing, and completely shading the ground.

Tall Fescue

It should be noted that Kerr et al. (1996) presented calibrated monthly K_c values less than 1 for Kentucky bluegrass. Since the turfgrass was well-watered and ET rates for periods of high precipitation were omitted from the data sets, the K_c should be equivalent to K_{cb}. From the discussion by Kerr et al. (1996), it appeared the turfgrass' average height was less than 5 inches. Depending on the year and the month, a K_{cb} of approximately 1 was measured at least once for all months except October, although the average monthly K_{cb} values were less than 1.0. During the early spring and late fall, the ET rates will be most likely less than reference because the grass is not actively growing as required for reference conditions and thus K_{cb} values would be expected to be less than 1.0. Another factor to be considered is the heat stress that Kentucky bluegrass experiences during hot weather. This could explain part of the low values for K_{cb} during July and August. Considering all factors, it still appears that a K_{cb} of 1.0 is a good estimate for well-watered, actively growing, and adequately fertilized cool-season grasses.

Kentucky Bluegrass

In many situations, turfgrass is not always well maintained, especially turfgrass used in parks or other public areas. The authors believe a K_{cb} of 0.9 or 0.85 can be justified for low maintenance cool-season grasses or if grasses are maintained at an average height of 3 inches or less. The paper by Mecham (1996) demonstrated that short clipped (3 inches) cool-season grass would have approximately 10 percent less ET than grass maintained at an average height of 5 inches. Biran et al. (1981) found tall fescue and perennial rye grass had a 20 percent decrease in ET rates between a mowing height of 2.4 and 1.2 inches. Feldhake et al. (1983) reported a 14 percent decrease in ET rates when Kentucky bluegrass mowing height changed from 2 inches to just less than 1 inch with the same frequency of mowing. Feldhake et al. (1983) also reported ET ratés 14 percent lower for Kentucky bluegrass with deficient nitrogen.

Maintenance Factors

For both cool- and warm-season grasses, one could reduce the K_{cb} values by 0.1 (for example, 0.9 rather than 1.0 for a high maintenance, cool season grass) for the first and last month of the growing season. The turfgrasses during these periods are not actively growing and would have reduced ET rates. The justification for this adjustment and recommendation is based on the research reported by Kerr et al. (1996).

Warm Season Grasses

Comparison To Cool-Season Grasses

Warm-season grasses are the predominant type of turfgrass used in Texas and includes bermudagrass (most common cultivars are Arizona common, Tifgreen, and Tifway), St. Augustine grass (cultivar Texas common), zoysiagrass (cultivar Emerald and Meyer), and buffalograss (cultivar Texas common). These grasses are C4 (metabolism) grasses (Kim and Beard, 1988). All warm-season grasses, in general, have approximately the same ET rates and are approximately 80 percent of the ET rates for cool-season grasses (Kim and Beard, 1988). Feldhake et al. (1983) reported bermudagrass ET rates at 79 percent of ET rates for Kentucky bluegrass. Note, however, the tests were conducted in Colorado where warm- season grasses seldom over-winter. Carrow (1995) found ET rates for common bermudagrass to be 82 percent of that for tall fescue grass. In addition, Carrow (1995) reported ET rates for St. Augustine, Tifway bermudagrass, and Meyer zoysiagrass to be 89, 84, and 96 percent respectively, of the ET rate for tall fescue. Evapotranspiration rates of 82, 81, 90, and 91 percent of ET rates for tall fescue were reported by Kim and Beard (1988) for bermudagrass, buffalograss, zoysiagrass, and St. Augustine grass, respectively. Kopec et al. (1990) found a K_c value of 0.83 for summer and 0.72 for winter for bermudagrass using a grass reference crop evapotranspiration equation. For high maintenance bermudagrass, Kneebone and Pepper (1983) reported ET rates of 91 percent of that for tall fescue.

Bermuda-grass

For planning purposes, it appears the best K_{cb} value for bermudagrass is 0.80 for average maintenance and 0.85 to 0.9 for high maintenance bermudagrass. There does not appear to be much difference between the ET rates for bermudagrass for areas with low humidity (Kneebone and Pepper, 1983) versus areas with high humidity (Carrow, 1995).

Low Maintenance

It is important to note that Kneebone and Pepper (1983) found low maintenance bermudagrass' ET rates to be 72 percent of the ET rates for tall fescue. Similarly, Devitt et al. (1992) reported golf courses (high maintenance) had 29 percent greater ET rates than did parks (low maintenance) for bermudagrass over-seeded with rye grass. It is thus recommended that the K_{cb} for low maintenance bermudagrass be 0.75 for planning purposes.

Buffalo-grass

For buffalograss, the average K_{cb} appears to be 0.80, or the same as for bermudagrass (Feldhake et al. 1983; Kim and Beard, 1988). The authors could find no data on experimental results for buffalograss grown under high maintenance since it is generally recommended for low or average maintenance environments (Duble, 1988).

St. Augustine Zoysiagrass

Based on the results of Kim and Beard (1988) and Carrow (1995), the K_{cb} for St. Augustine grass and zoysiagrass is estimated to be 0.90 for average and high maintenance conditions. These grasses are generally used in residential lawns, and a K_{cb} of 0.9 would be appropriate.

Contours of Grass Mean Monthly Evapotranspiration Rates

Shown in Figures 32 - 36 are ET_{crop} contours for the various K_{cb} values. The user must decide on species of grass and the level of maintenance based on the information given above. Values of ET_{crop} for turfgrasses can then be read directly from Figures 32 - 36. Four irrigations per month were assumed for March through October. One irrigation per month was assumed for the months of November through February.

Growing Season for Turfgrasses

Temperatures For Warm-Season Grasses

Determining the growing season for turfgrasses is difficult. It would appear that except in the far northern portion of Texas, cool-season grasses stay green essentially all year when adequately irrigated. This does not mean there is active photosynthesis occurring. The plants are green and evapotranspiration is still occurring. Warm-season grasses turn brown losing their chloropyll content when the mean temperatures go below 55 to 60 °F (Beard, 1973). In these cases, evaporation still occurs as long as there is significant moisture in the soil. Kneebone et al. (1979) reported measured ET from Kentucky bluegrass in the latter part of December at rates of near 0.04 inches per day—a value close to wet-bare soil evaporation. Furthermore, in the early spring, green shoots are beneath the thatch and evapotranspiration occurs one to two months before the turf has significant green leaf material at the surface (Kneebone et al., 1979).

Estimating the growing season for turfgrass is an exercise fraught with danger. Nevertheless, Beard (1973) estimates growth occurs for warm season turfgrasses at mean temperatures above 55 °F, and for cool-season turfgrasses above 40 °F. Above these temperatures growth occurs and below these temperatures the plants are quiescent (Unruh et al., 1996).

Unruh et al. (1996) published the basal growth mean temperatures for several common species of warm-season turfgrasses. When the mean temperature is below the basal growth temperature, there will be no growth. The basal growth temperatures for several species of turfgrass are presented in Table 19.

Basal Growth Temperatures

Table 19.- Basal Growth Temperatures for Warm-Season Turfgrasses, Adapted from Unruh et al. (1996).

Specie	Cultivar	Basal Growth Temperature (°F)
Bermudagrass	Arizona	40.8
Bermudagrass	Midiron	37.5
Buffalograss	Kansas Common	34.5
Buffalograss	Texoka	39.7
Centipedegrass	Common	54.1
St. Augustinegrass	Floratam	37.0
St. Augustinegrass	Raleigh	34.2
Zoysiagrass	Meyer	43.2

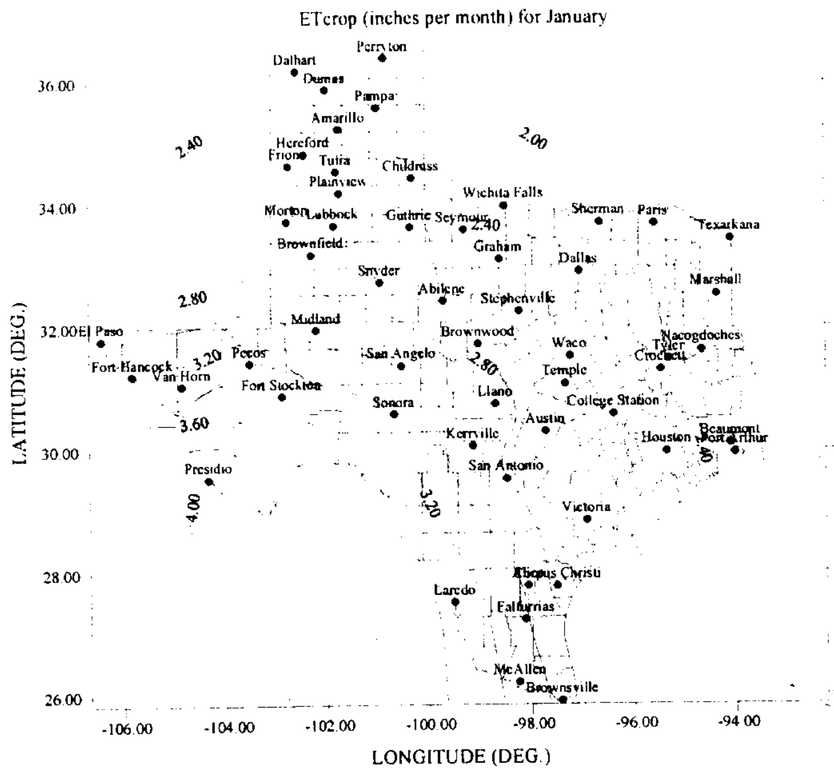
Mean temperature contours are presented in Appendix B (Figure B4) to aid in determining the growing season using the above criteria.

General Recommendations for K_{cb}

The ET rates for turfgrasses can vary by at least 25 percent depending on the specie selected and the maintenance of the turfgrass. People have noticed homes whose lawns have a dark green color and appeared to be precisely cut. Similarly, they have observed lawns with a light green color, that received very few if any irrigations and only need mowing once a month. Management is a factor and it is a judgment call by the planner in determining the level of management for turfgrasses. Shown in Table 20 are the recommended K_{cb} values for the common turfgrasses grown in Texas.

Table 20.- Recommended K_{cb} Values for Turfgrasses Under Various Maintenance Levels

Type of Grass	Maintenance Level	Recommended K_{cb}
Warm Season	High	0.90
Warm Season	Medium high	0.85
Warm Season	Average	0.80
Warm Season	Low	0.75
Cool Season	High	1.00
Cool Season	Medium	0.90
Cool Season	Medium, height 3 in.	0.85
Cool Season	Low	0.85



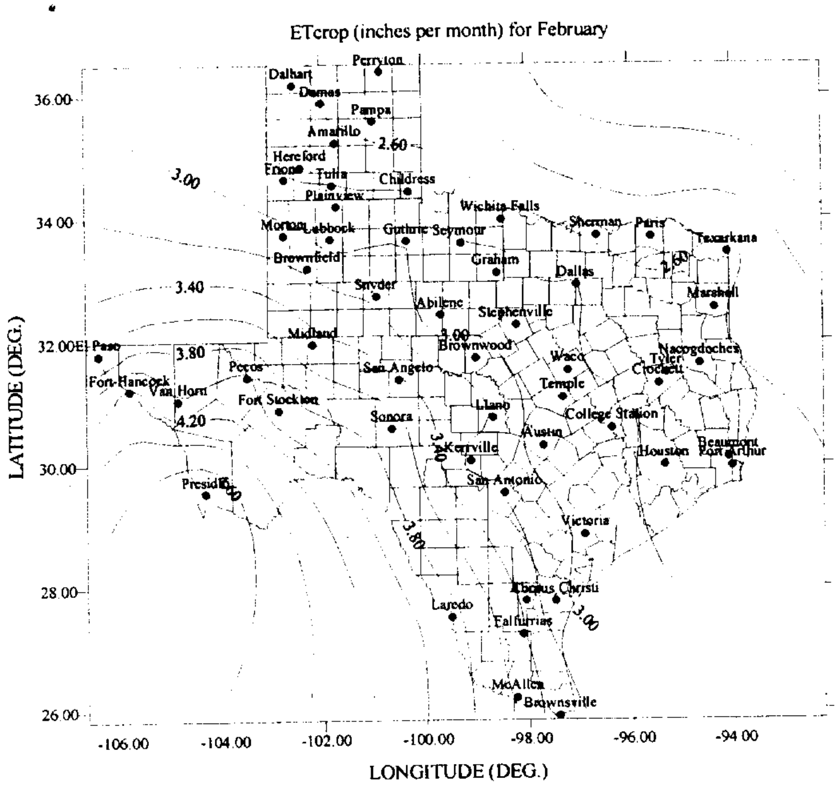
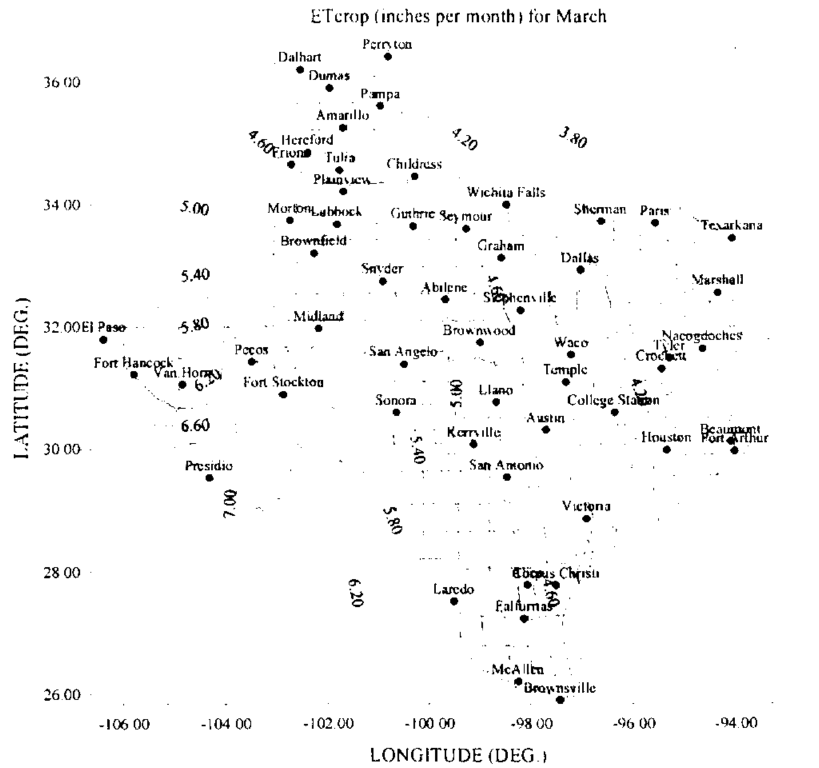


Figure 32.- ET_{crop} for Turfgrass with K_{cb}=1.0 (inches per month).



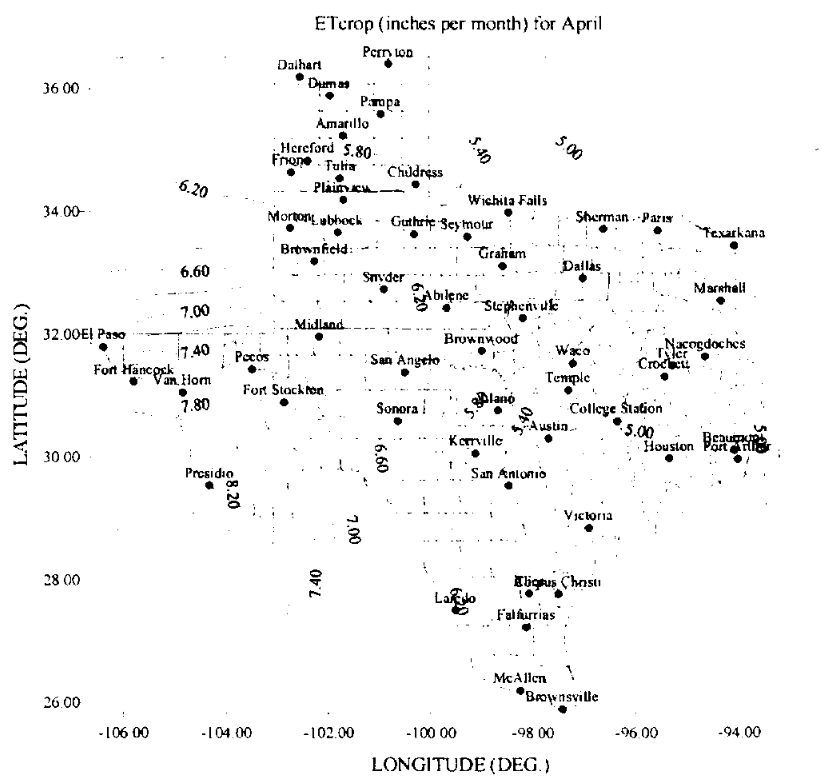
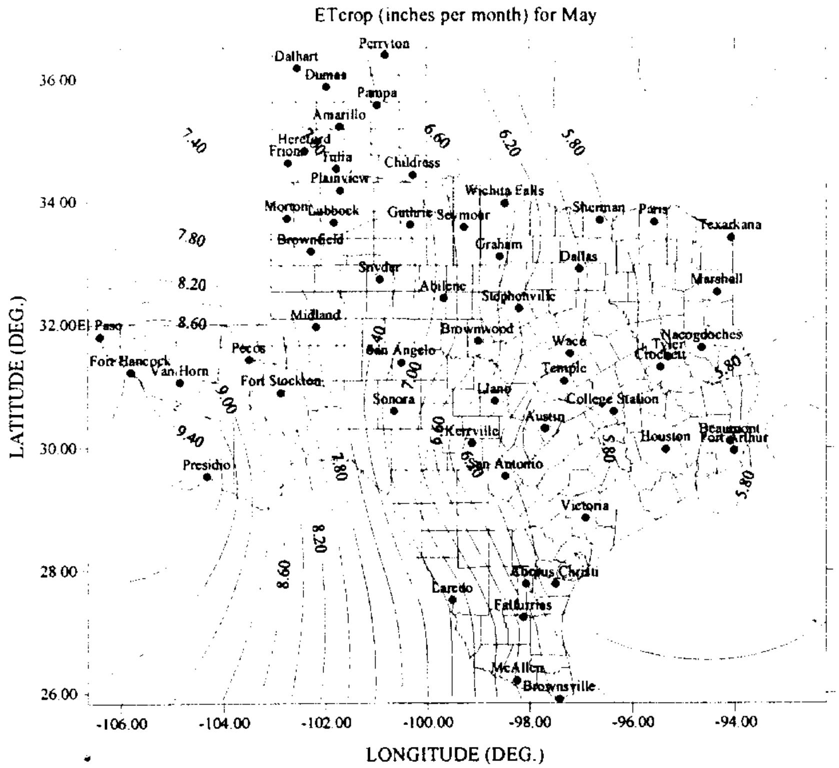


Figure 32.- ET_{crop} for Turfgrass with K_{cb}=1.0 (inches per month).



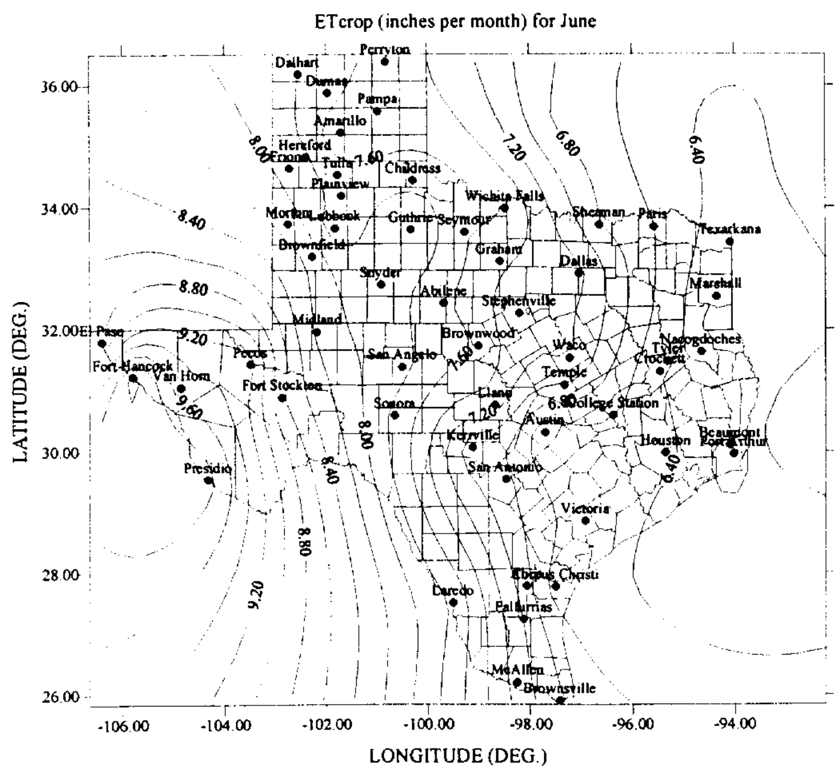
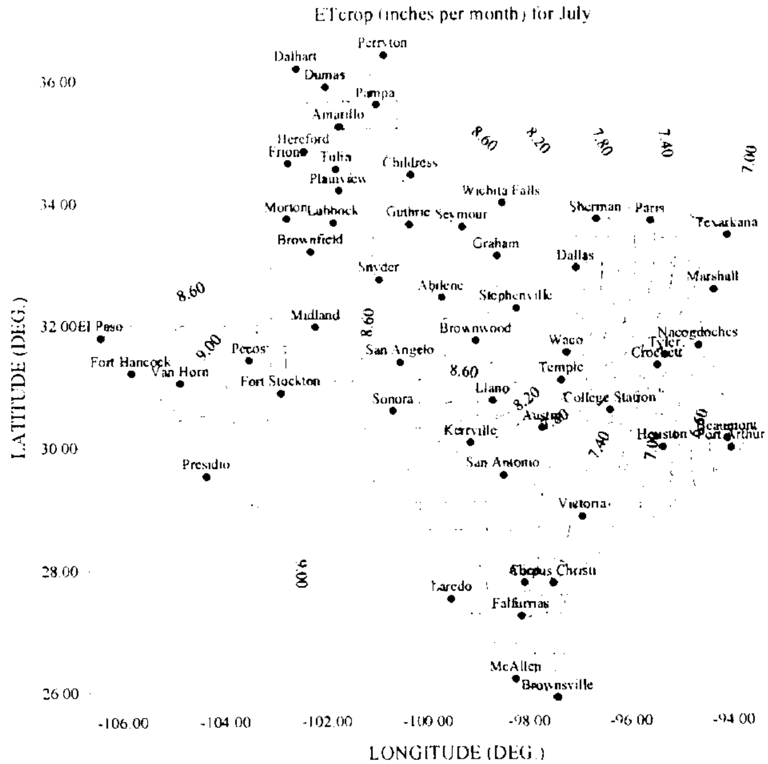


Figure 32.- ET_{crop} for Turfgrass with K_{cb} =1.0 (inches per month).



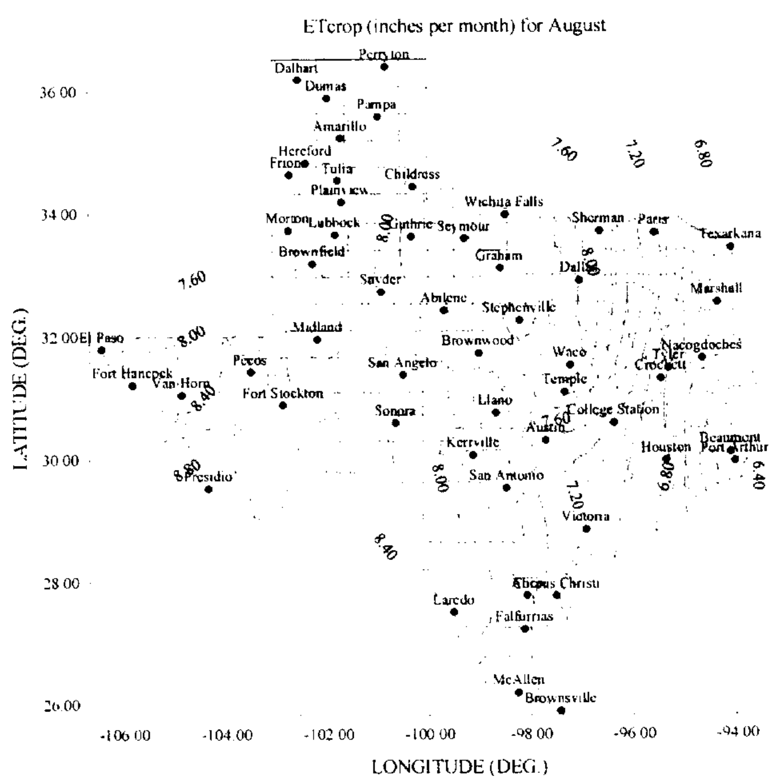
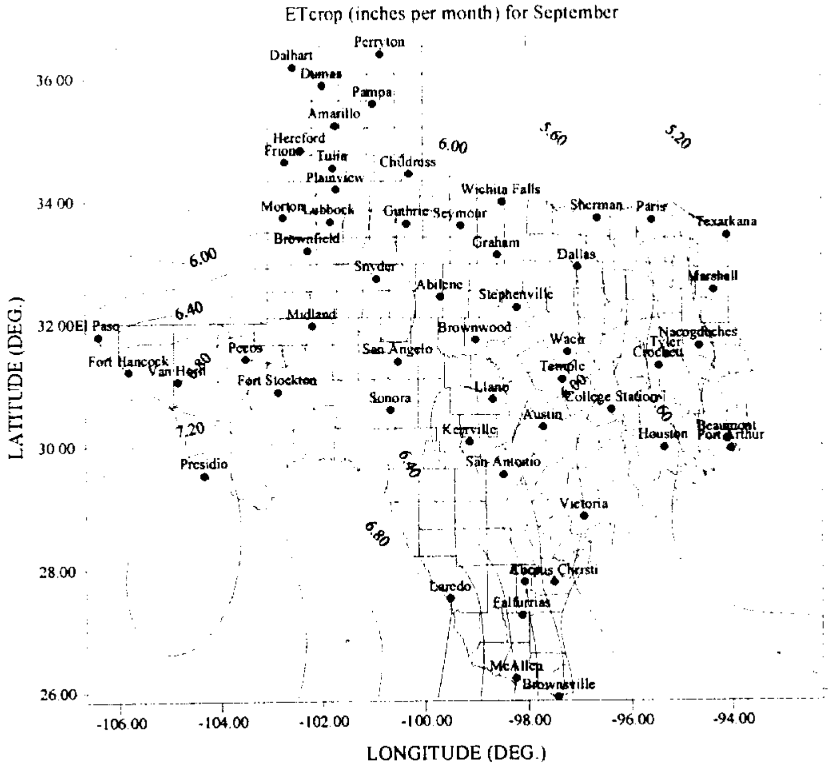


Figure 32.-ET_{crop} for Turfgrass with K_{cb}=1.0 (inches per month).



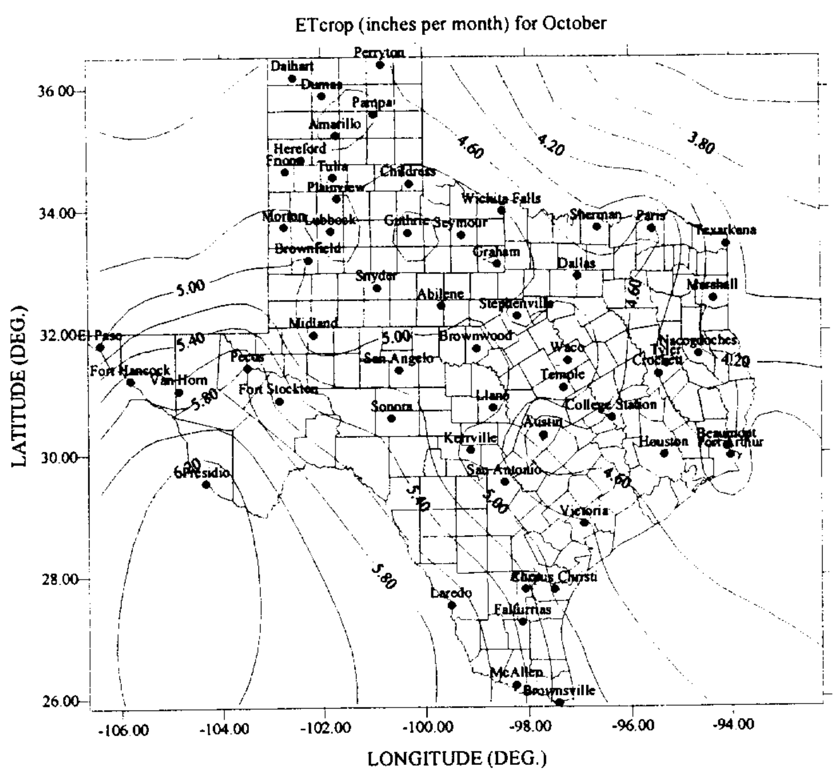
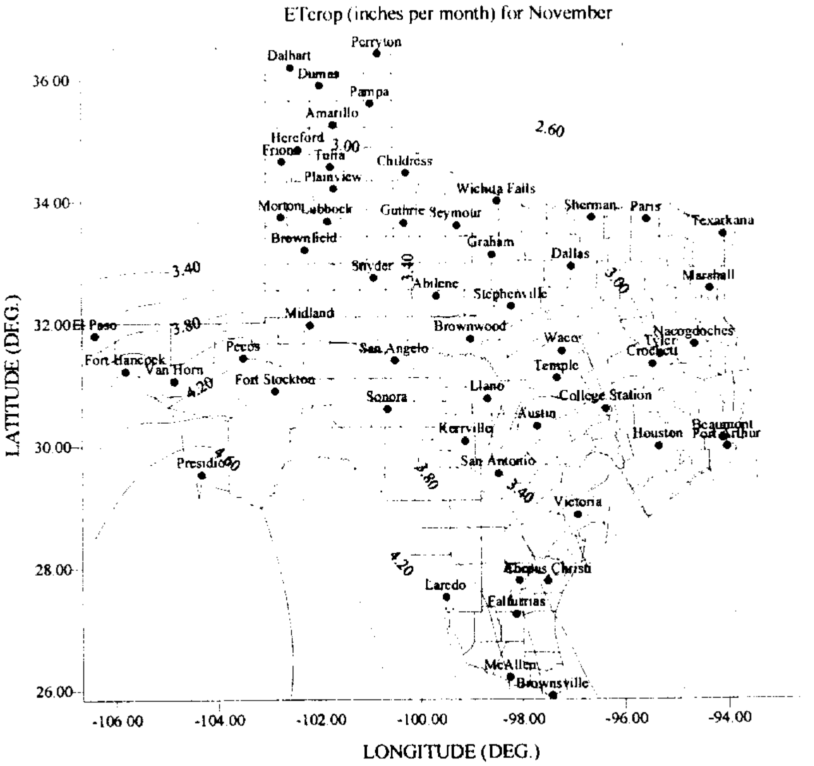


Figure 32.-ET_{crop} for Turfgrass with K_{cb}=1.0 (inches per month).



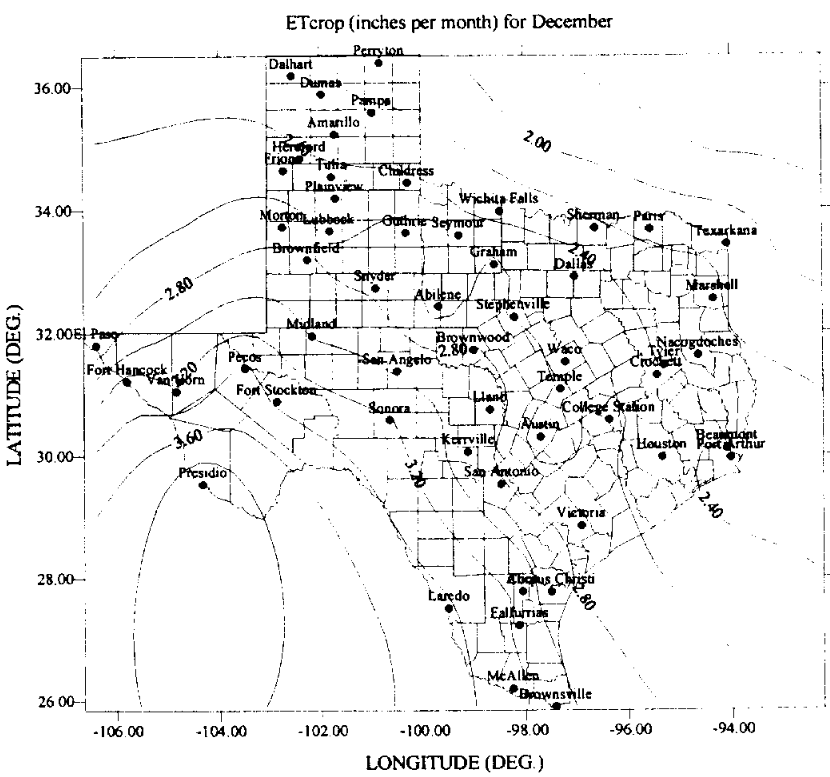
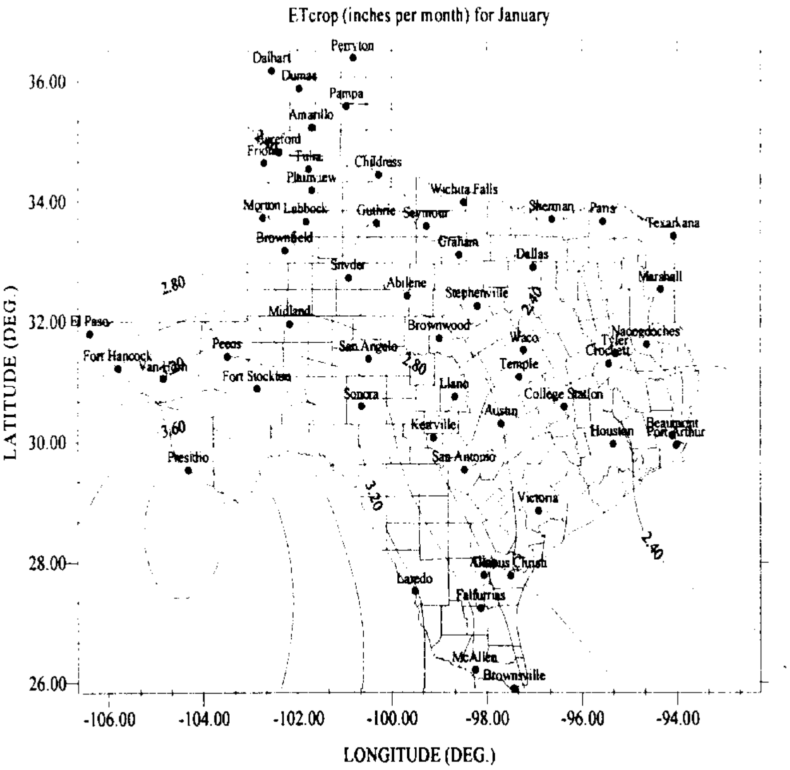


Figure 32.- ET_{crop} for Turfgrass with K_{cb} =1.0 (inches per month).



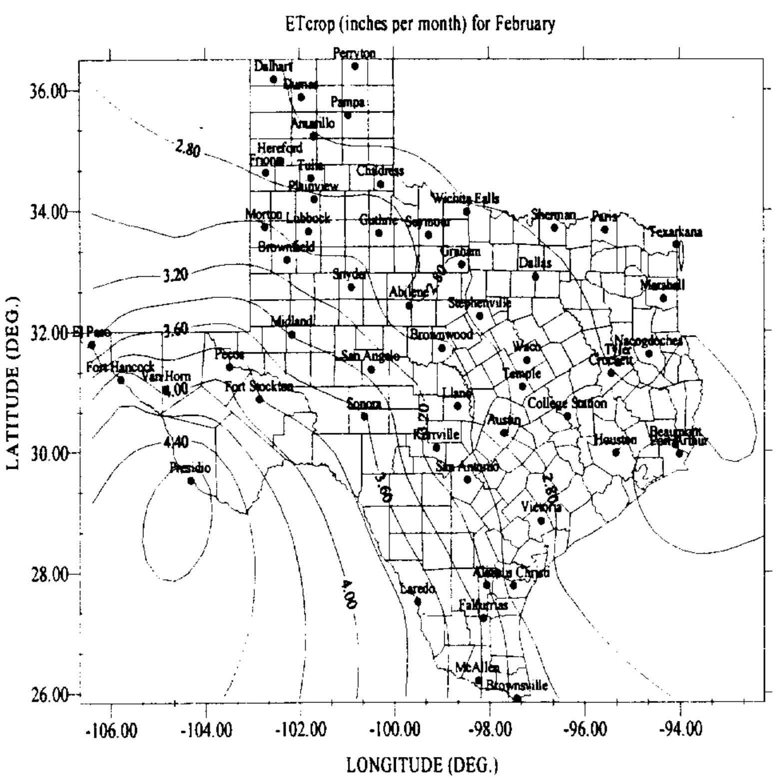
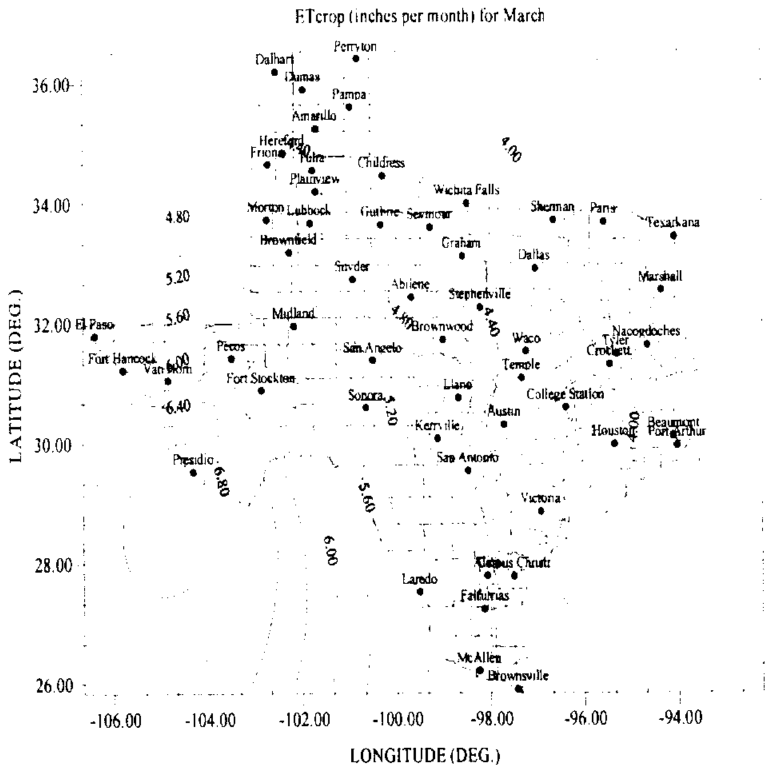


Figure 33.- ET_{crop} for Turfgrass with K_{cb}=0.9 (inches per month).



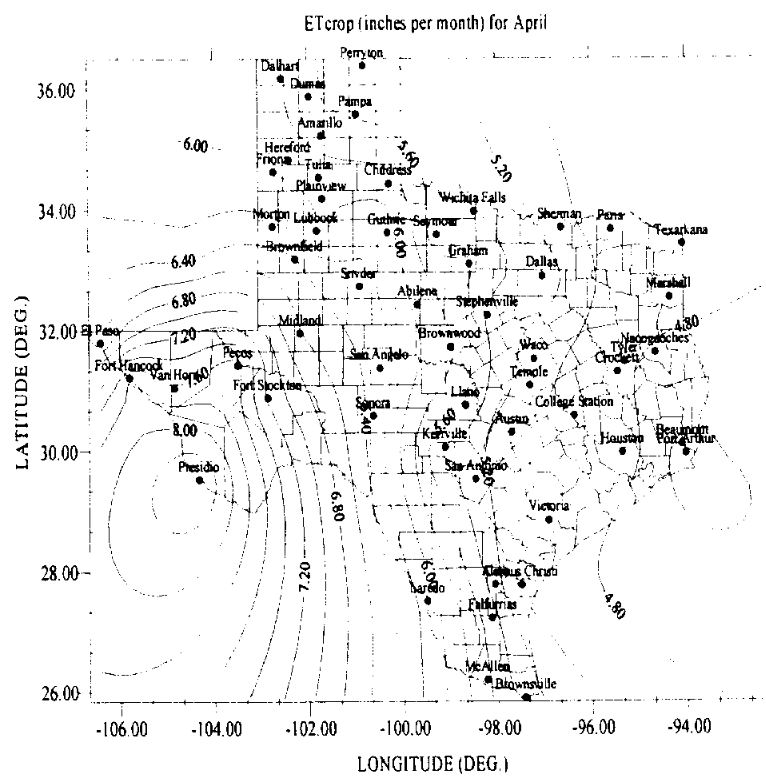
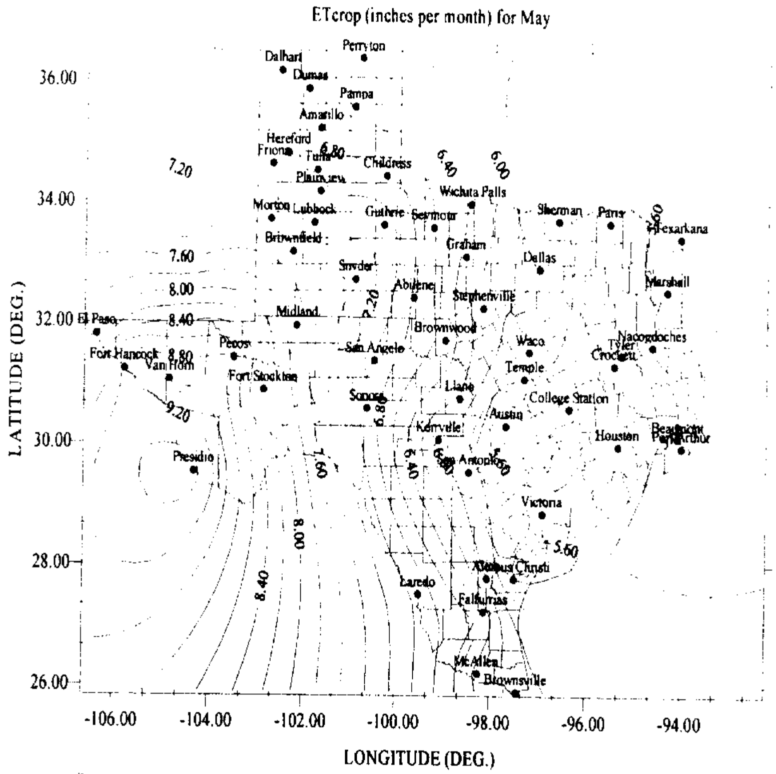


Figure 33.-ET_{crop} for Turfgrass with K_{cb}=0.9 (inches per month).



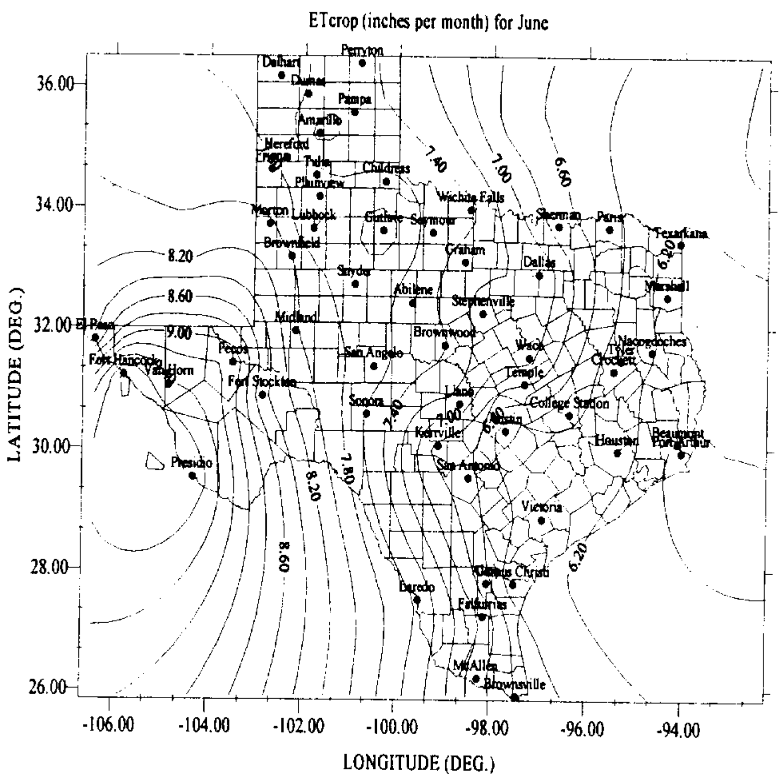
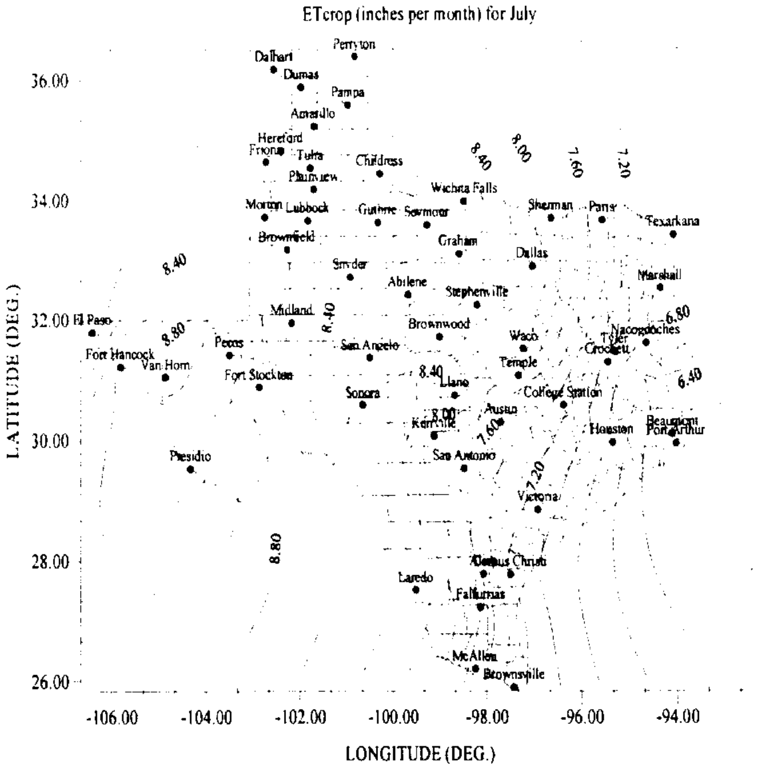


Figure 33.- ET_{crop} for Turfgrass with K_{cb}=0.9 (inches per month).



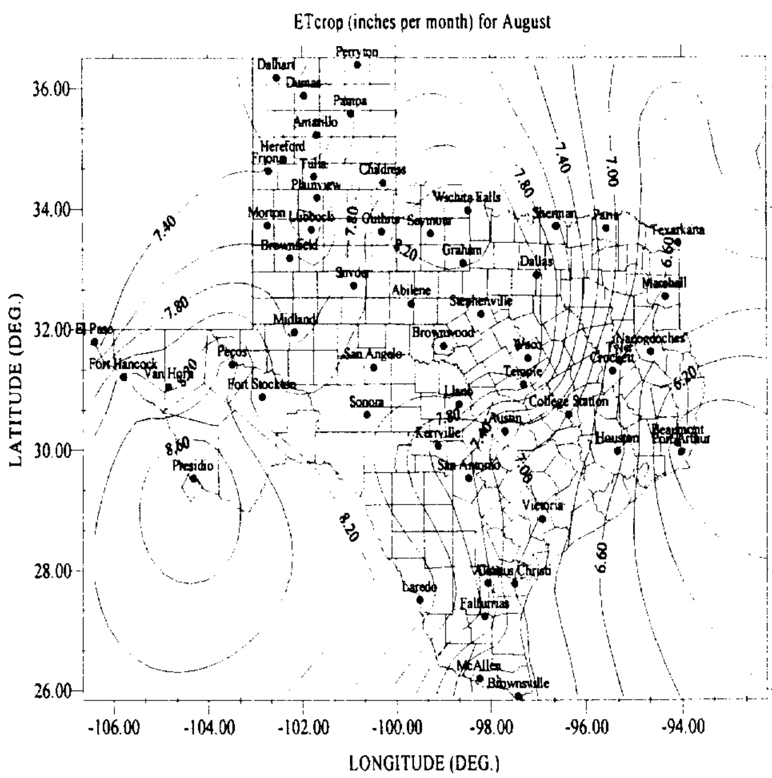
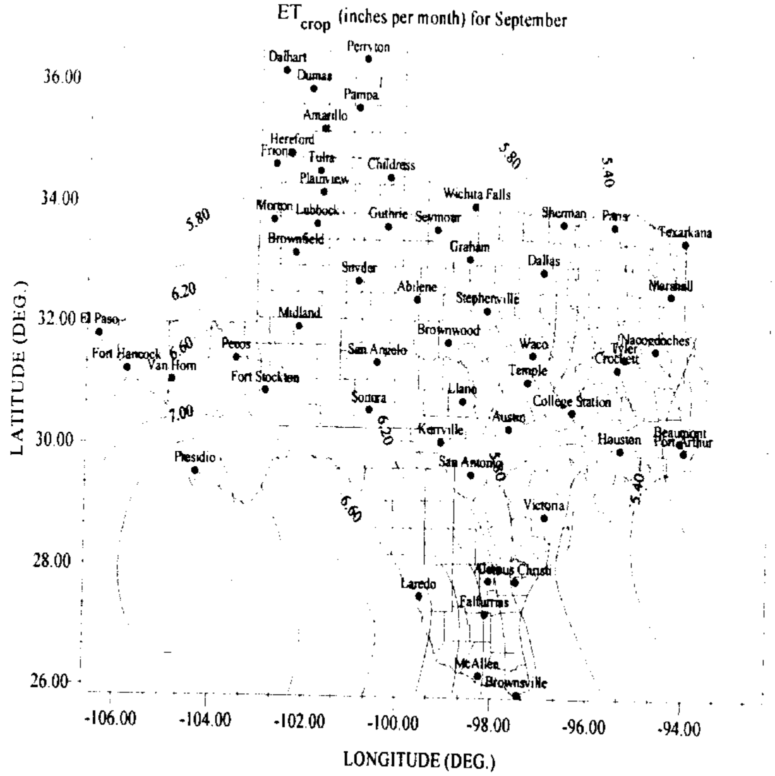


Figure 33.-ET$_{crop}$ for Turfgrass with K_{cb}=0.9 (inches per month).



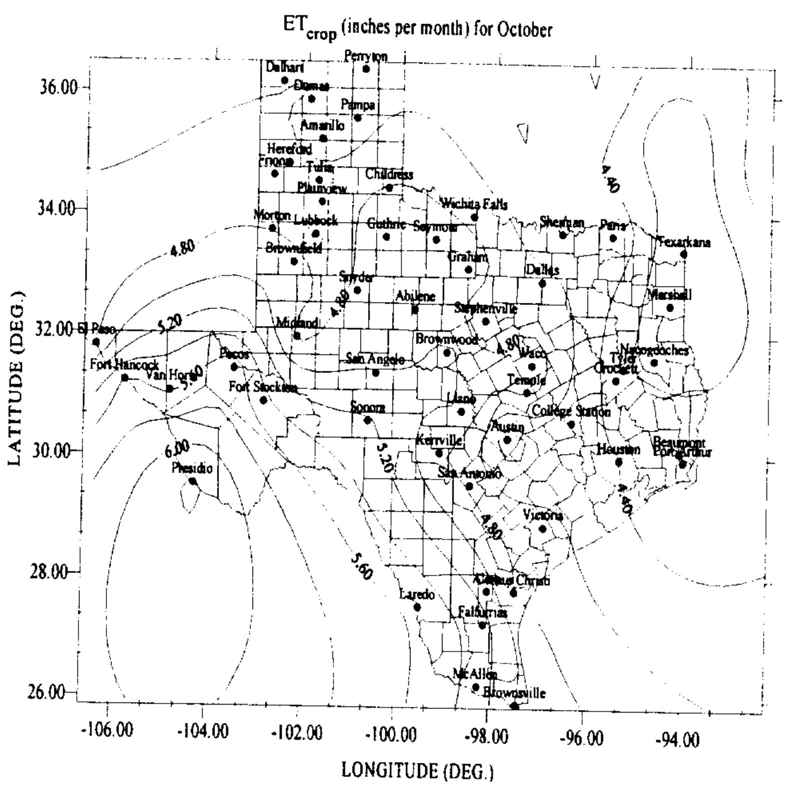
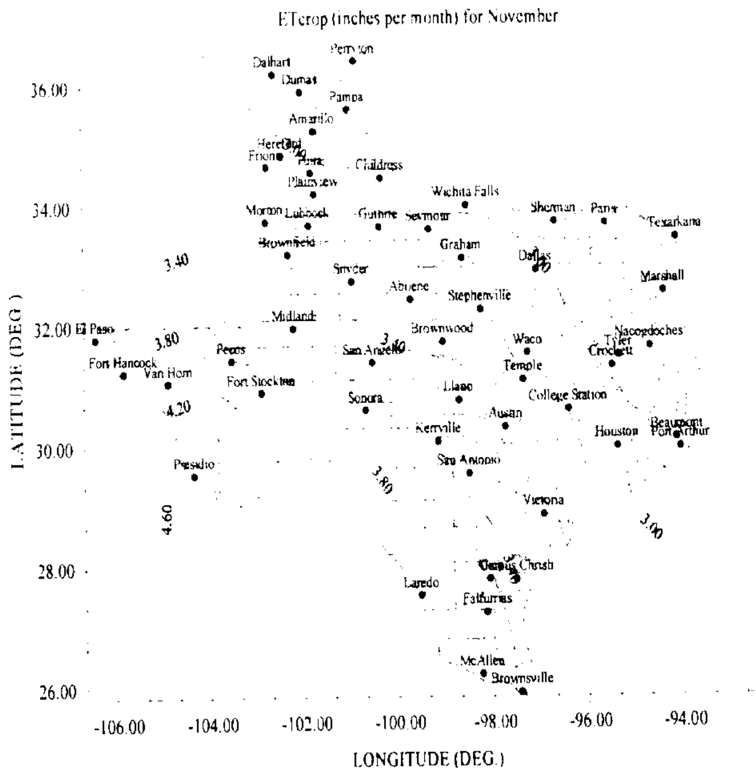


Figure 33.-ET_{crop} for Turfgrass with K_{cb}=0.9 (inches per month).



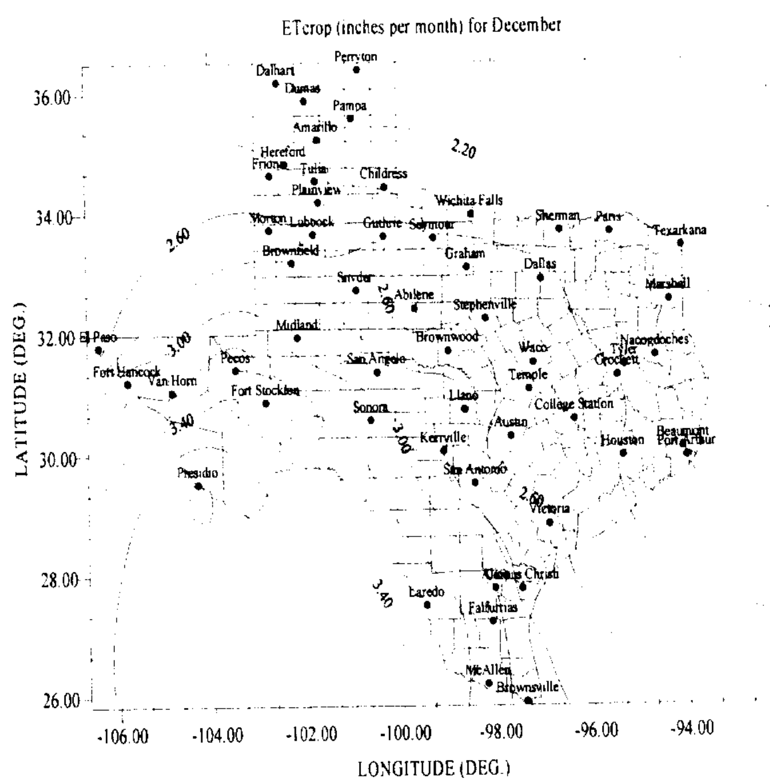
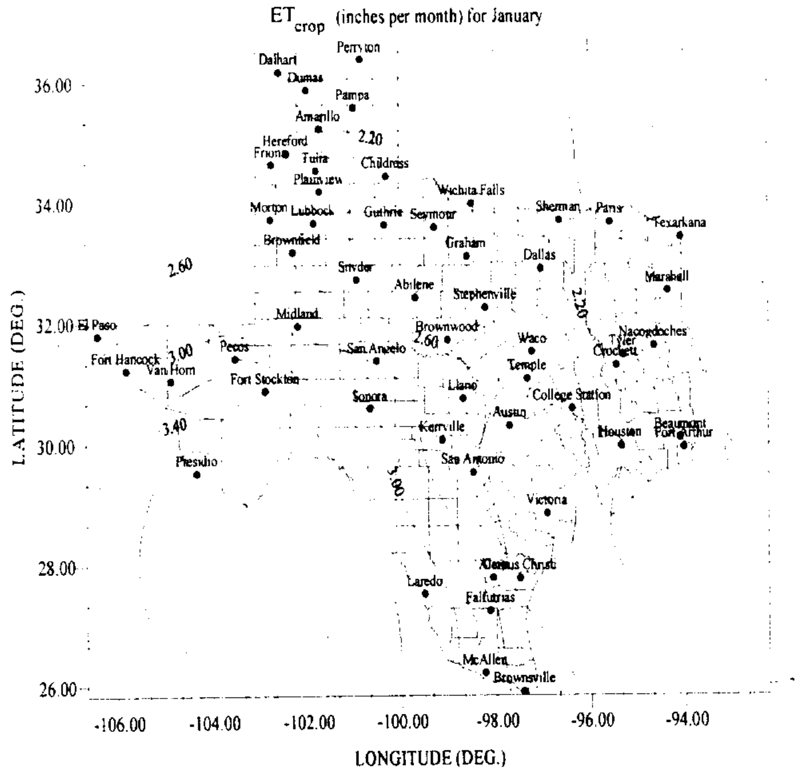


Figure 33.-ET_{crop} for Turfgrass with K_{cb}=0.9 (inches per month).



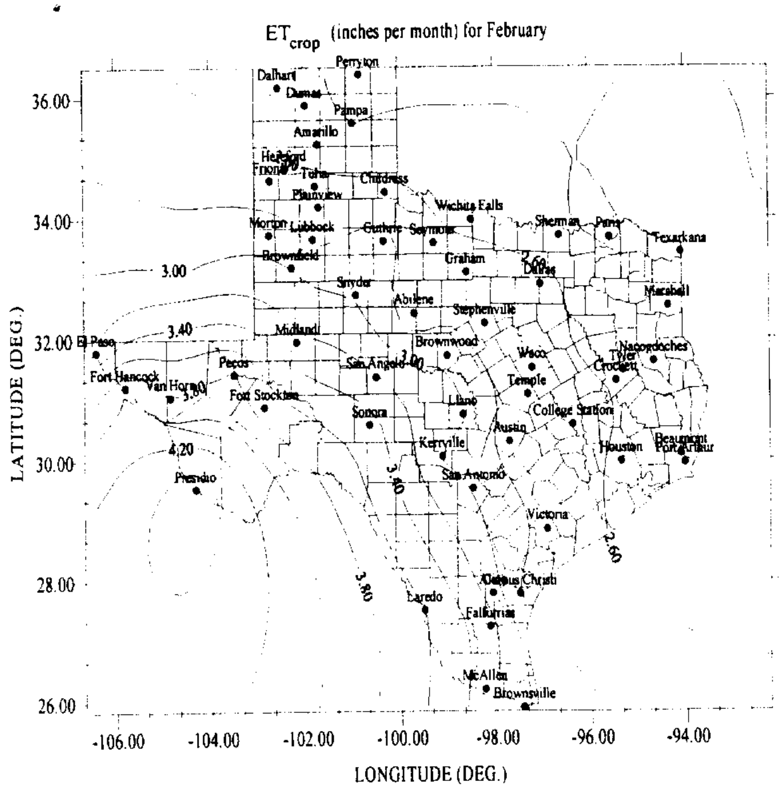
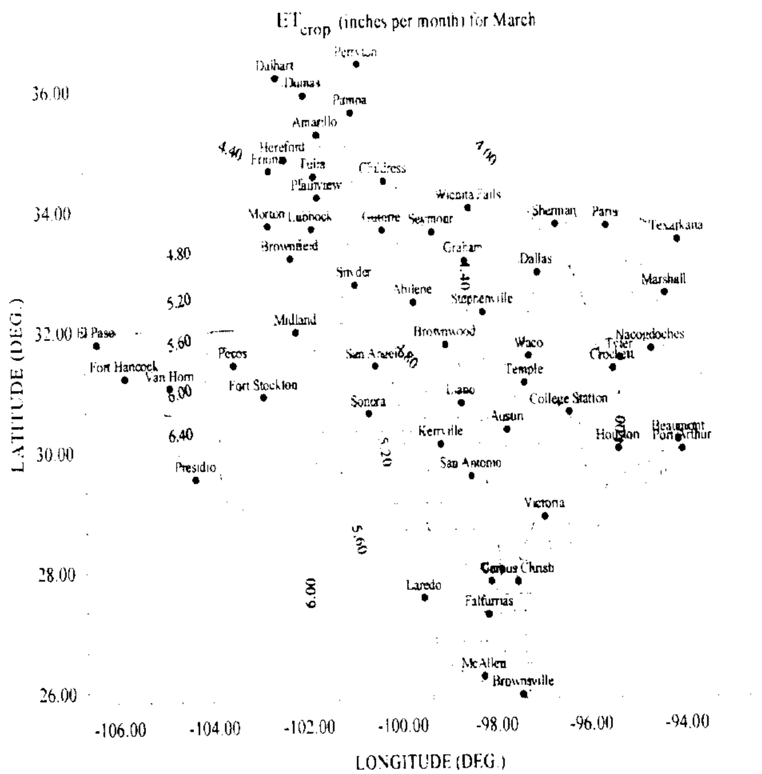


Figure 34.- ET_{crop} for Turfgrass with K_{cb}=0.85 (inches per month).



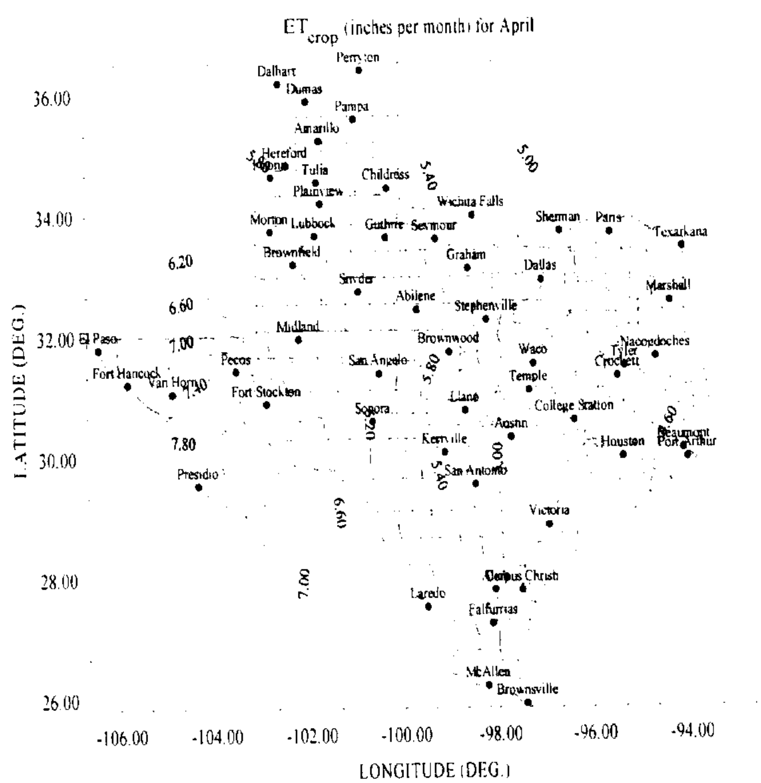
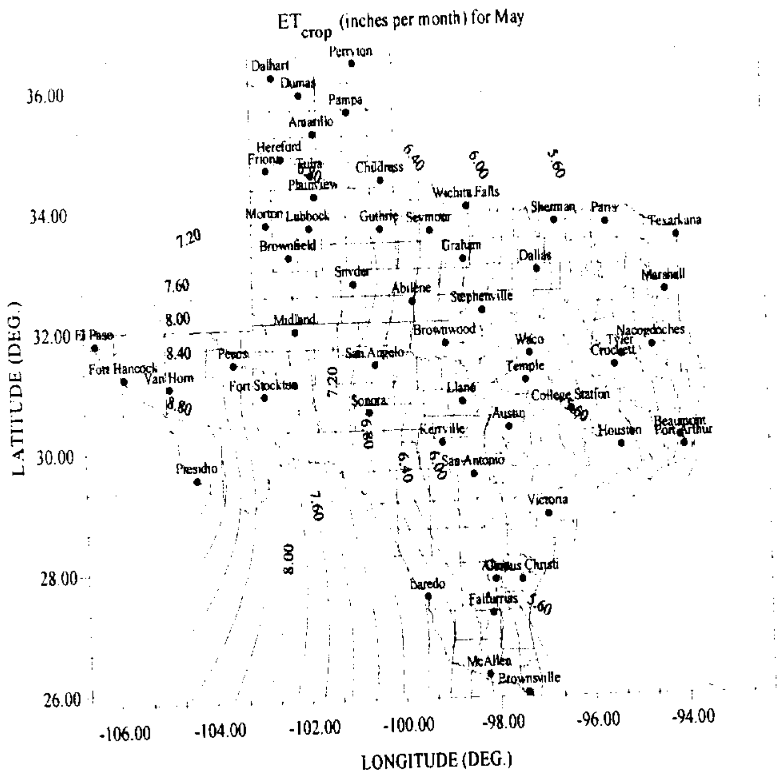


Figure 34.- ET_{crop} for Turfgrass with K_{cb} =0.85 (inches per month).



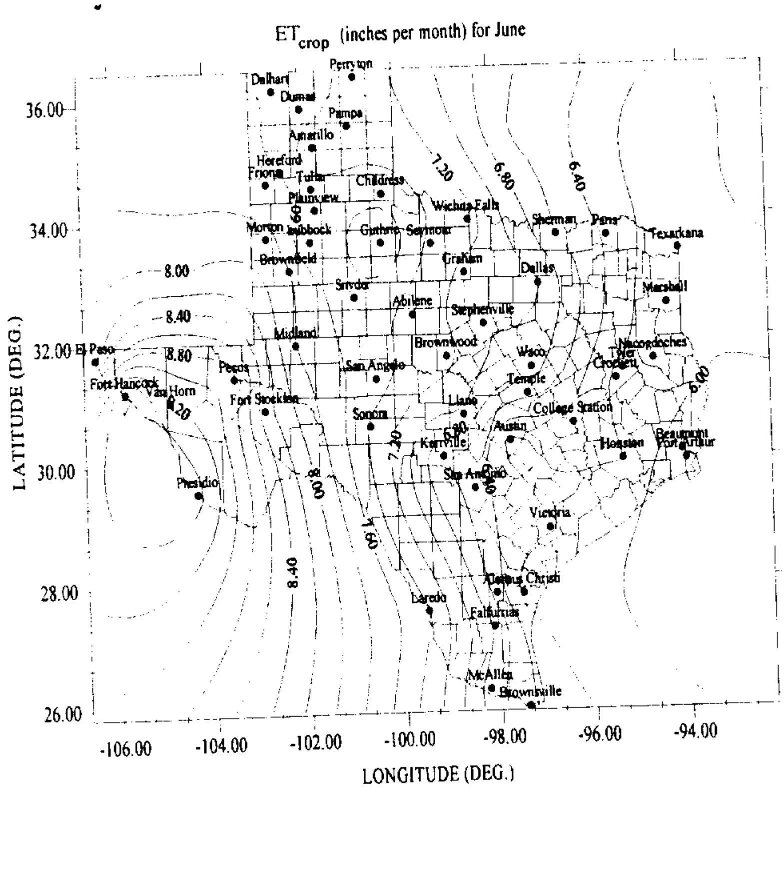
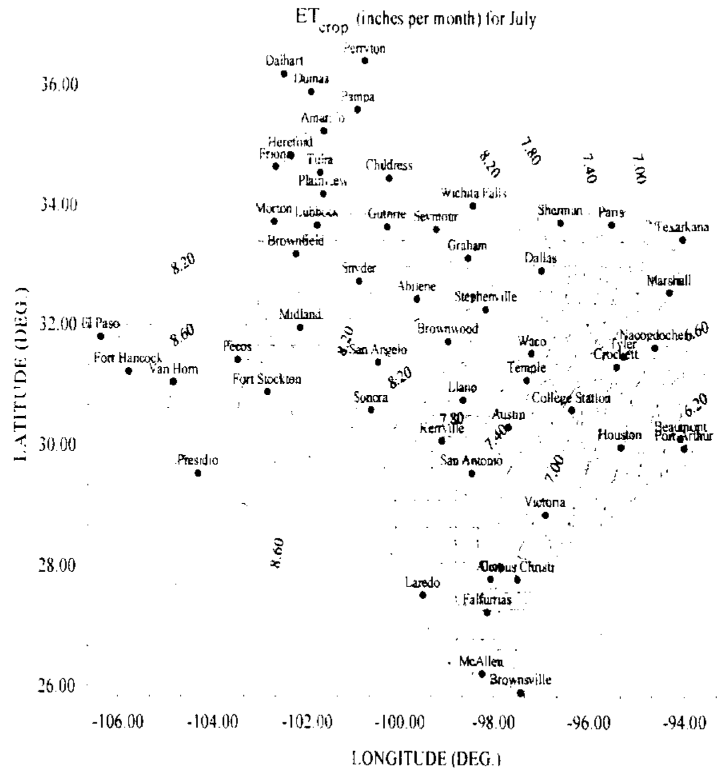


Figure 34.- ET_{crop} for Turfgrass with K_{cb}=0.85 (inches per month).



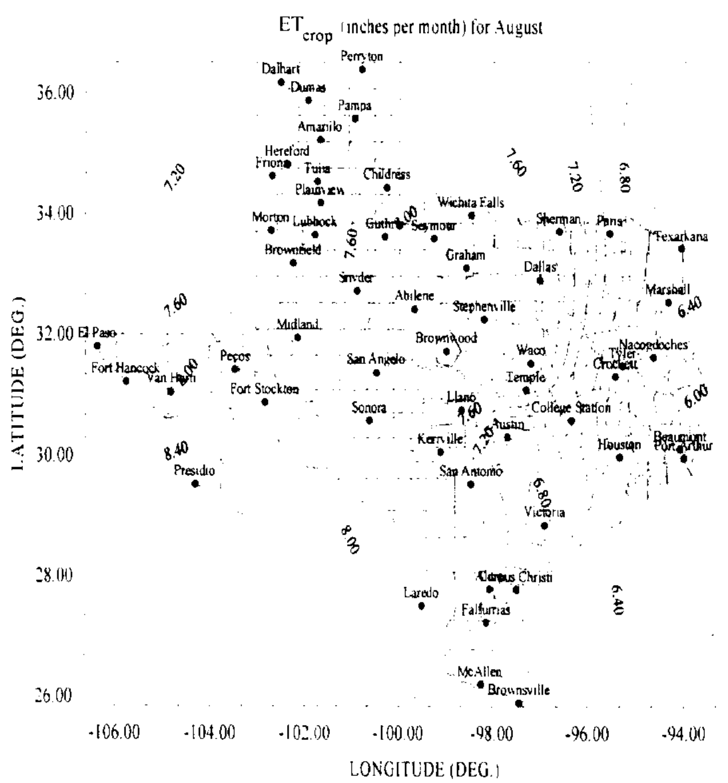
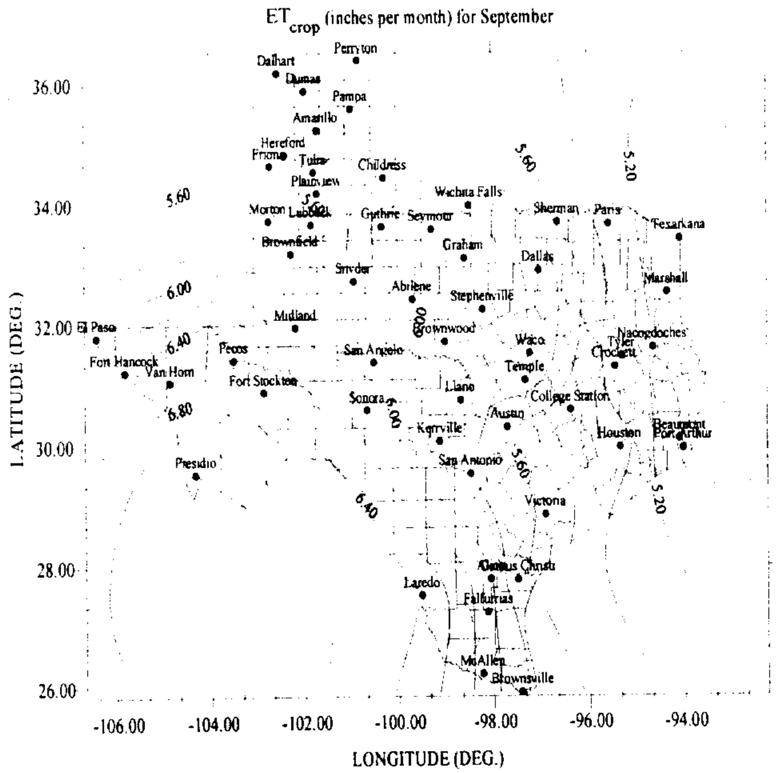


Figure 34.- ET$_{crop}$ for Turfgrass with K_{cb}=0.85 (inches per month).



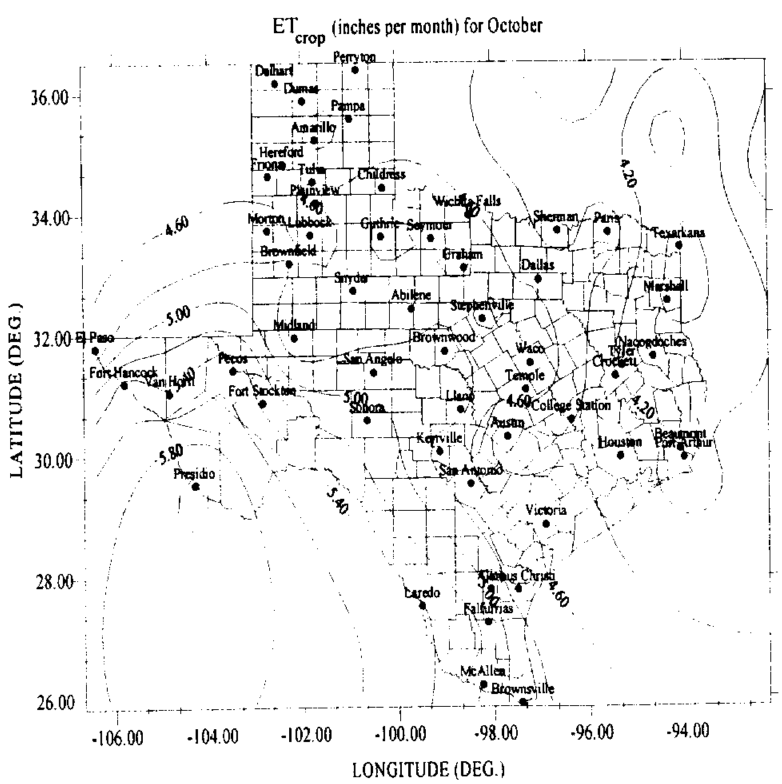
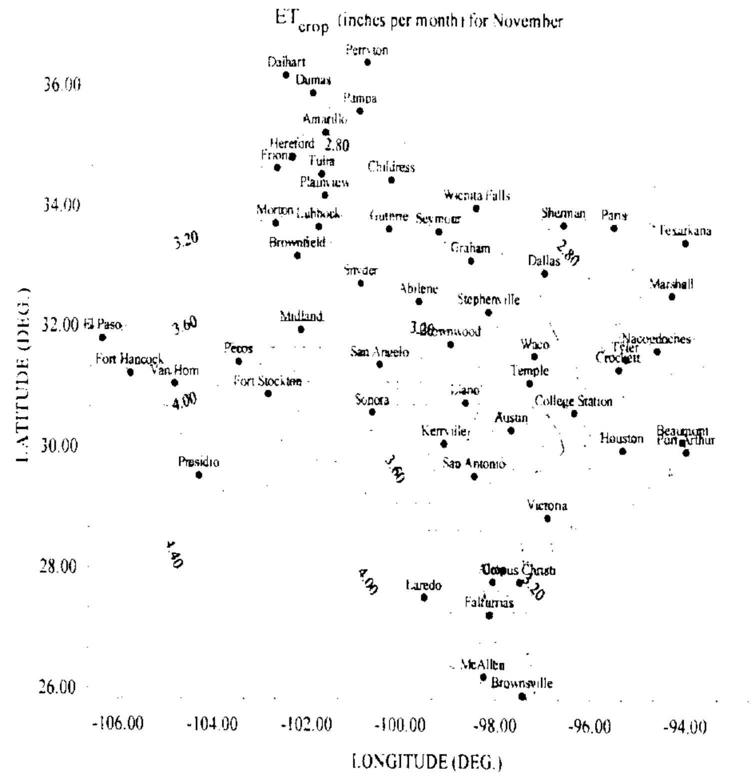


Figure 34.- ET_{crop} for Turfgrass with K_{cb}=0.85 (inches per month).



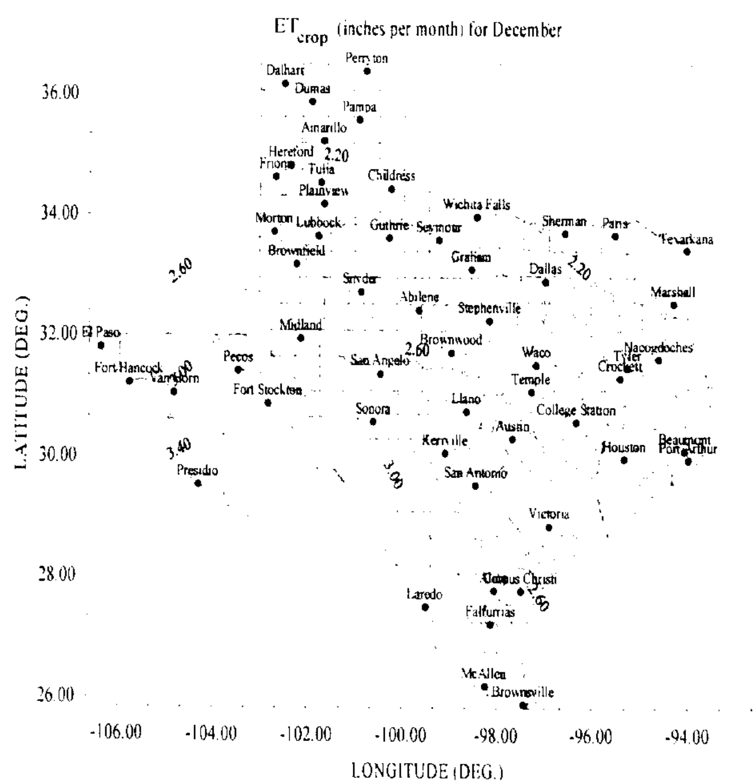


Figure 34.- ET$_{crop}$ for Turfgrass with K_{cb}=0.85 (inches per month).

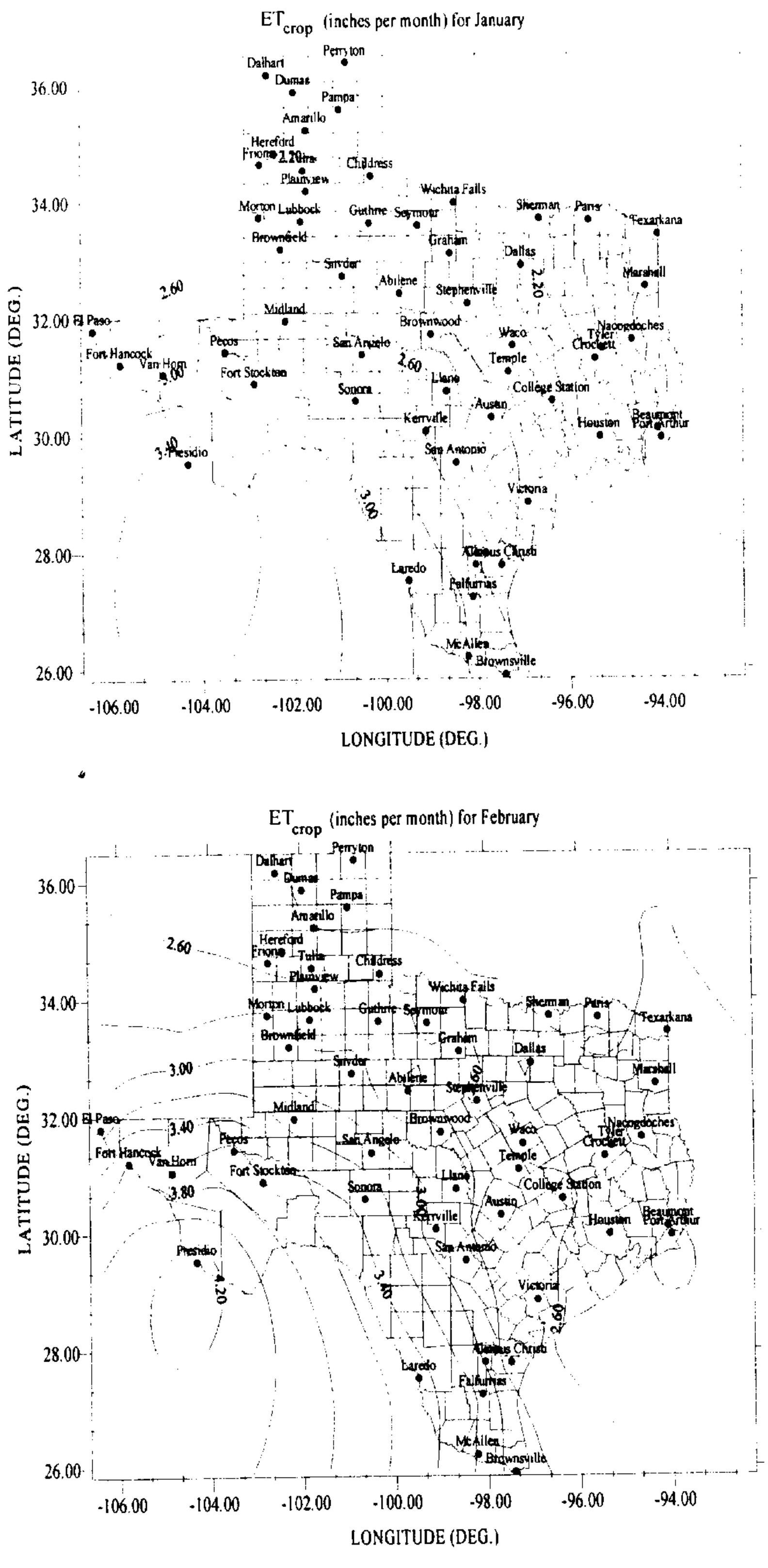


Figure 35.- ET_{crop} for Turfgrass with K_{cb}=0.8 (inches per month).

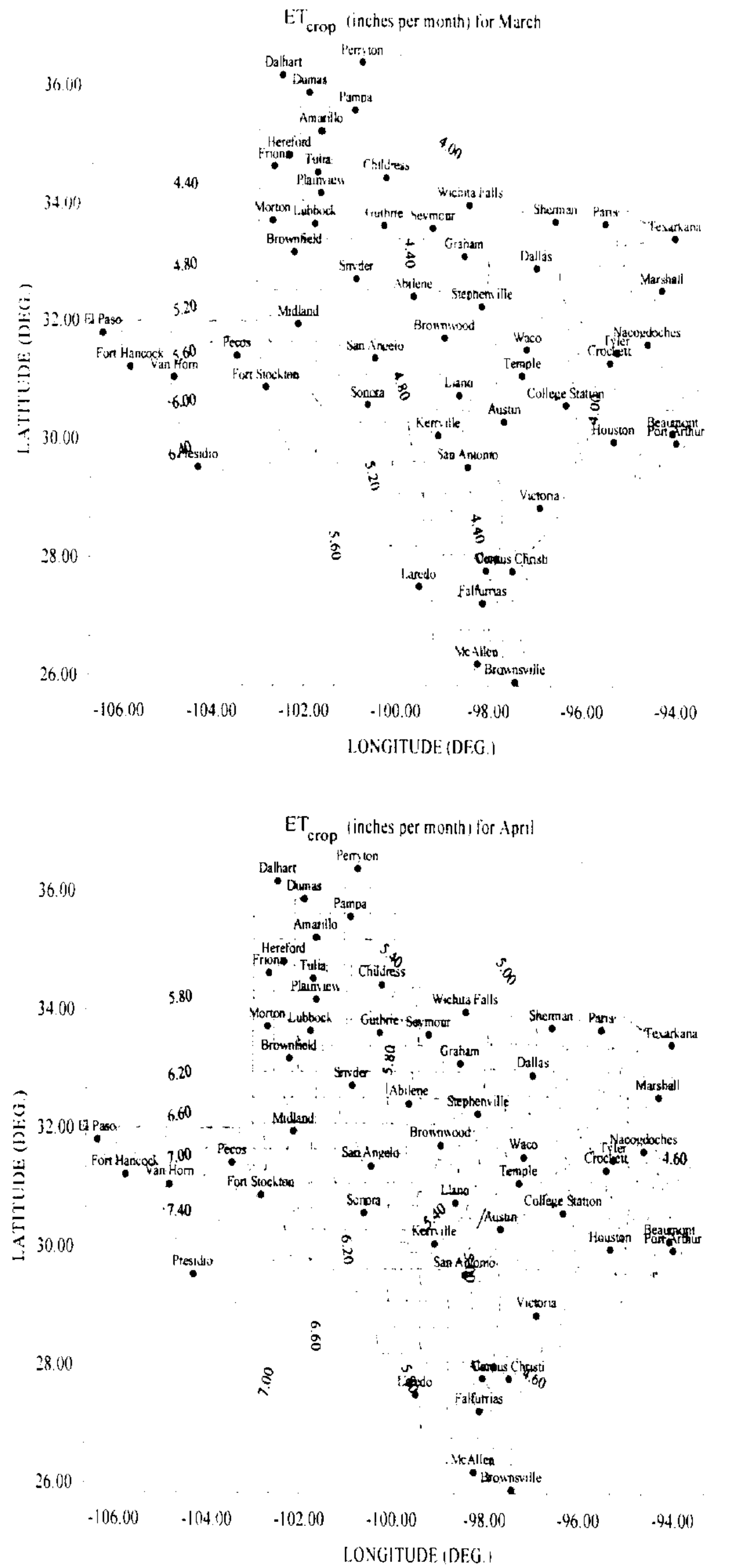


Figure 35.- ET_{crop} for Turfgrass with K_{cb}=0.8 (inches per month).

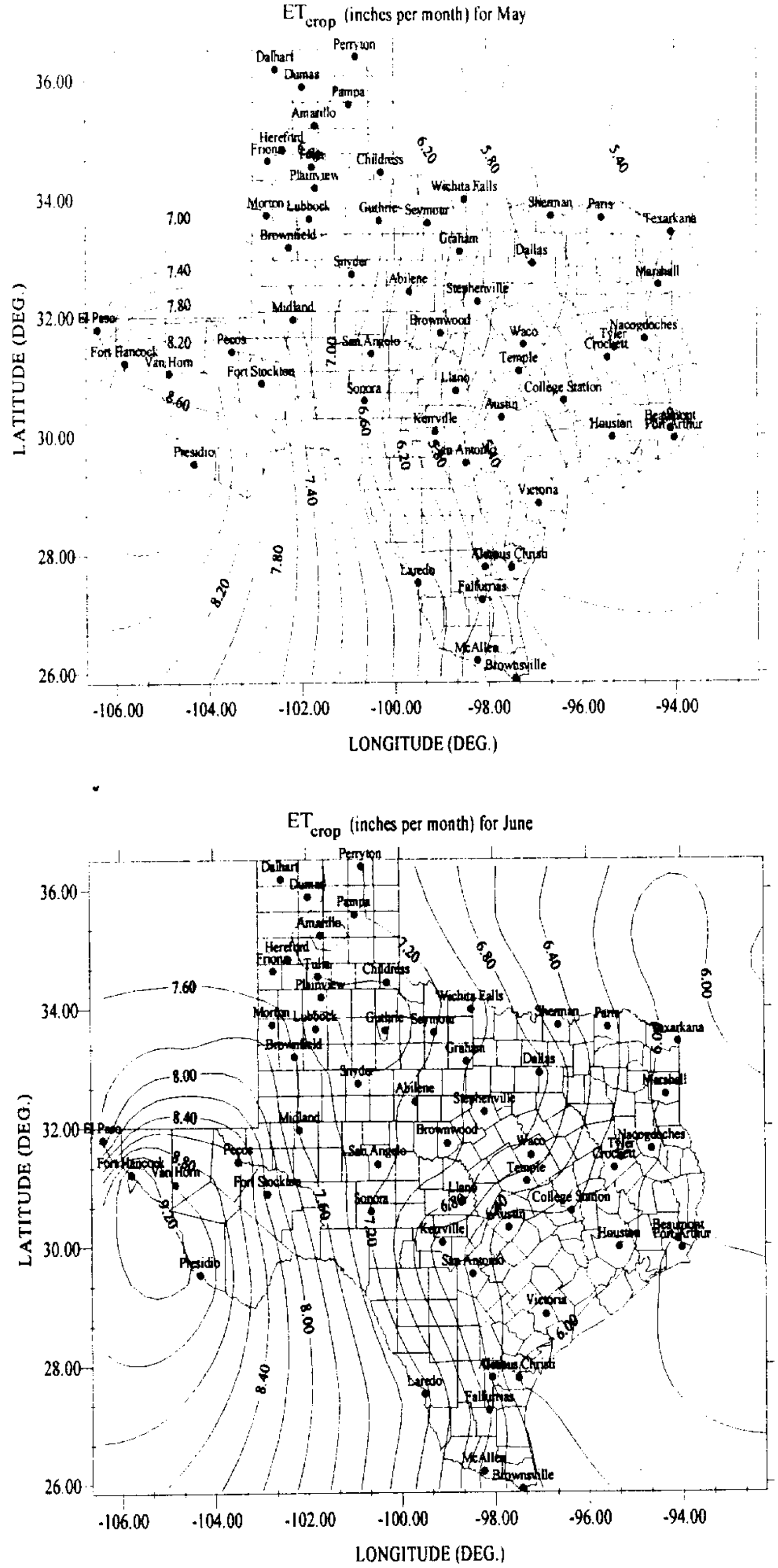
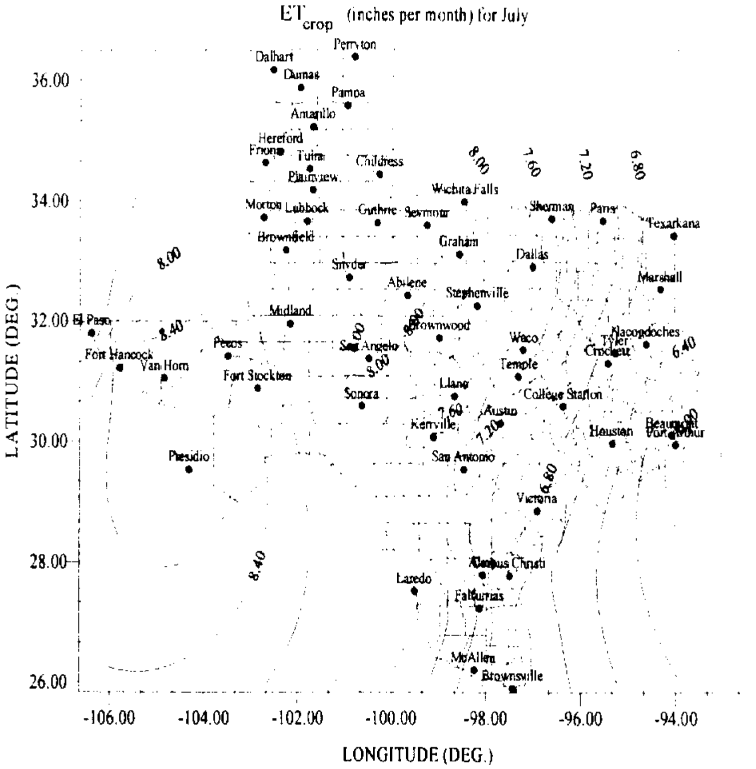


Figure 35.- ET_{crop} for Turfgrass with K_{cb}=0.8 (inches per month).



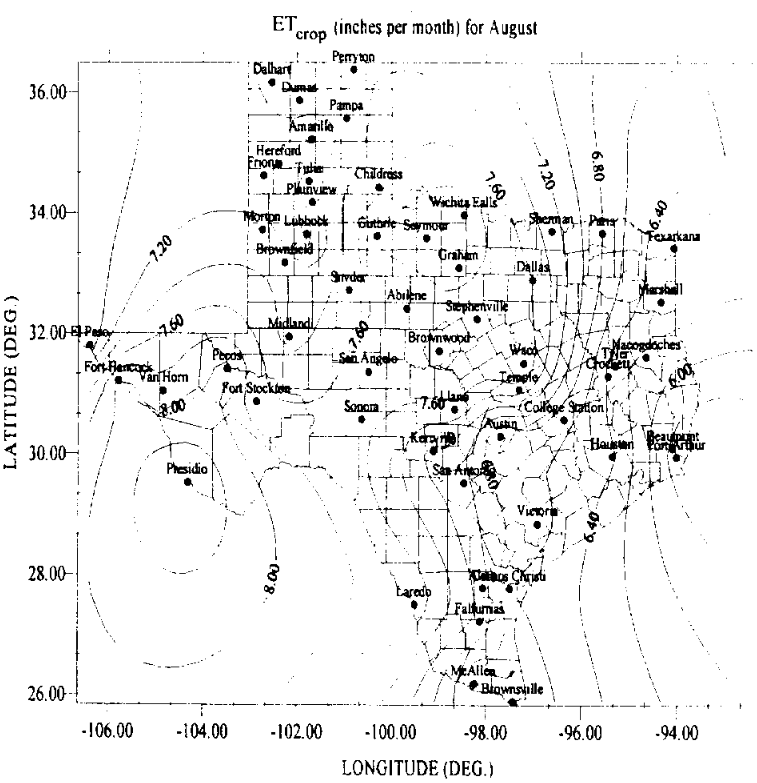
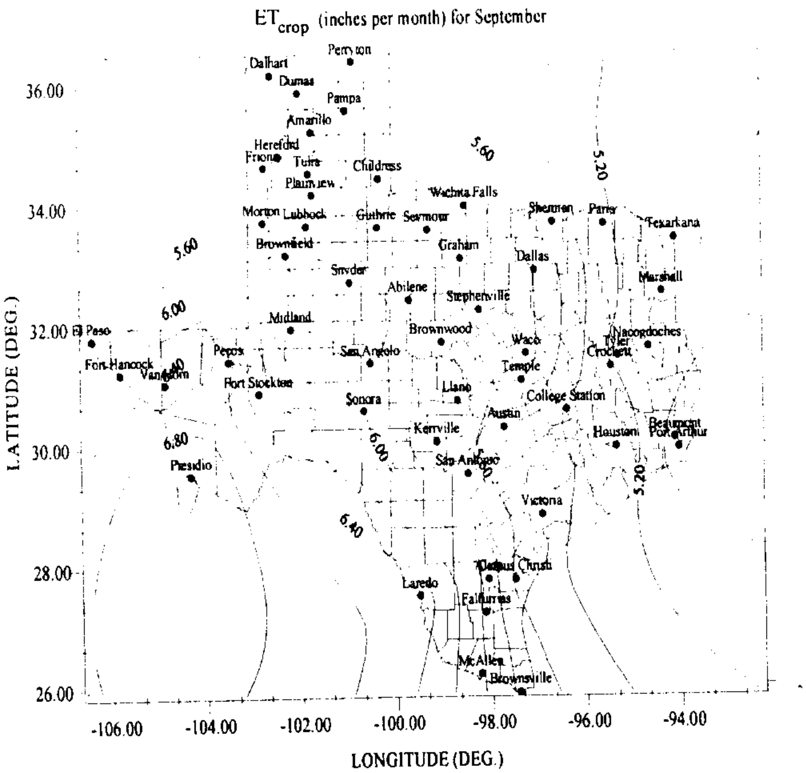


Figure 35.- ET_{crop} for Turfgrass with K_{cb}=0.8 (inches per month).



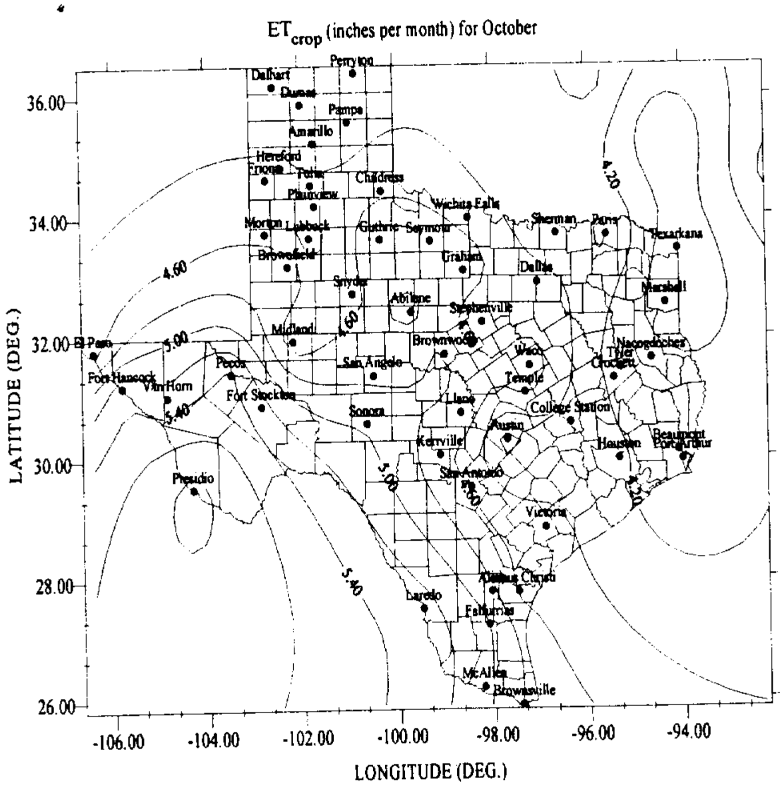


Figure 35.- ET_{crop} for Turfgrass with K_{cb}=0.8 (inches per month).

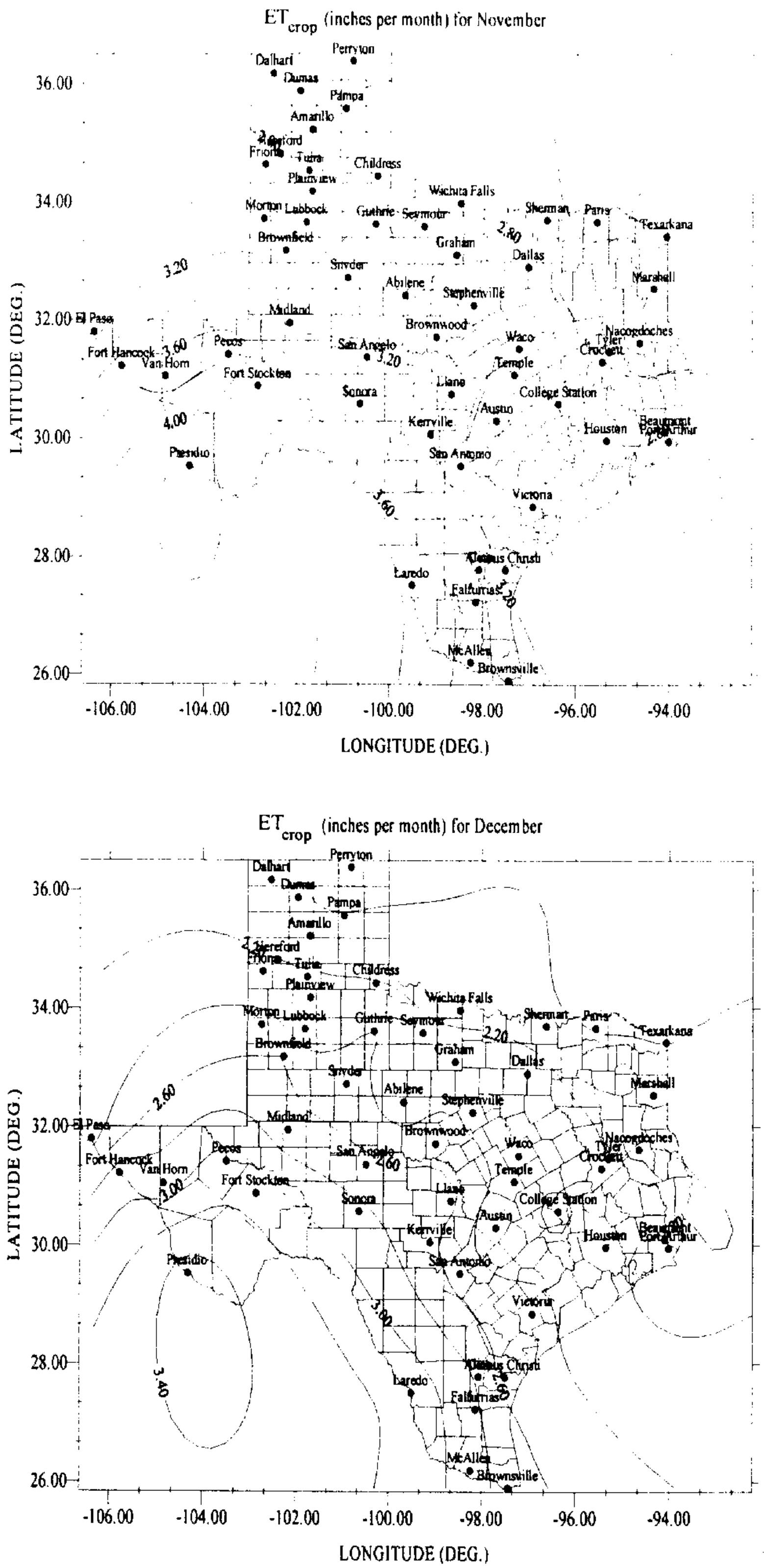
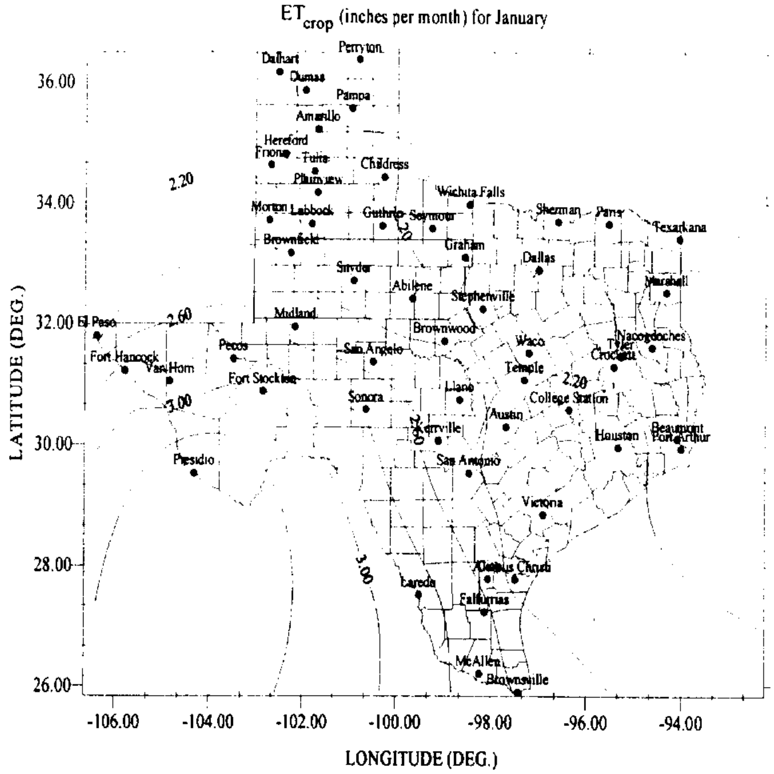


Figure 35.- ET_{crop} for Turfgrass with K_{cb}=0.8 (inches per month).



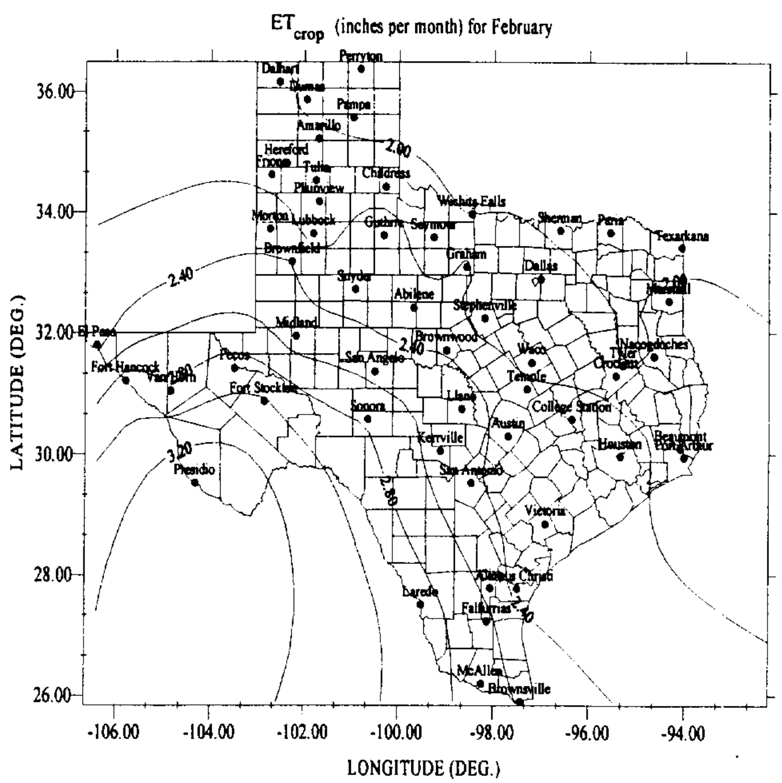
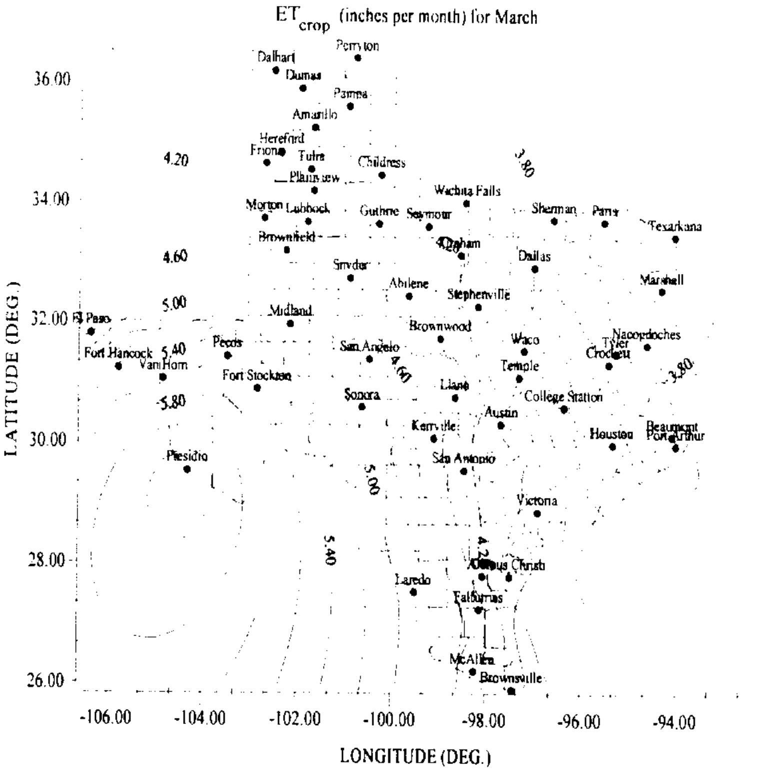


Figure 36.- ET_{crop} for Turfgrass with K_{cb}=0.75 (inches per month).



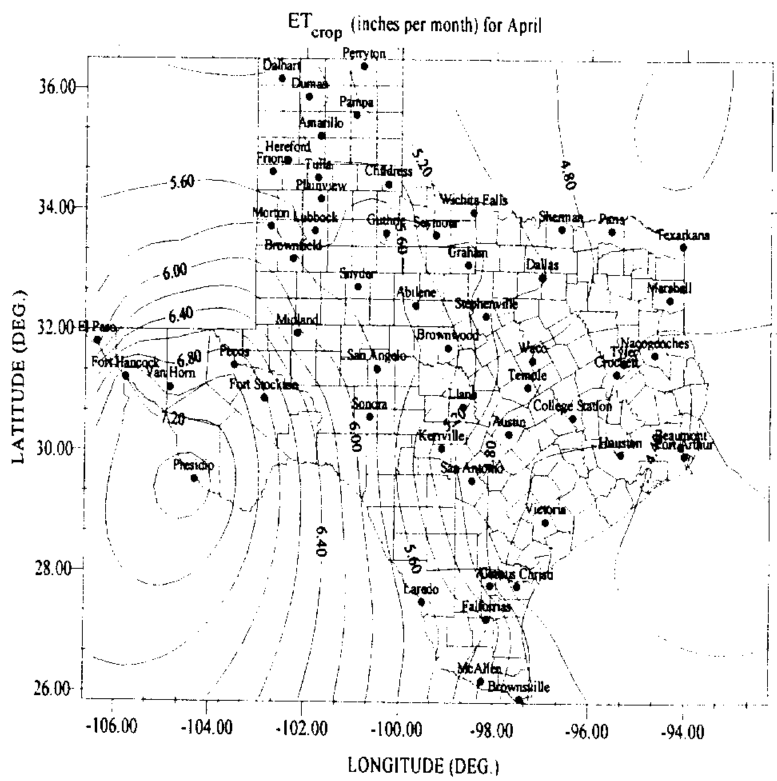
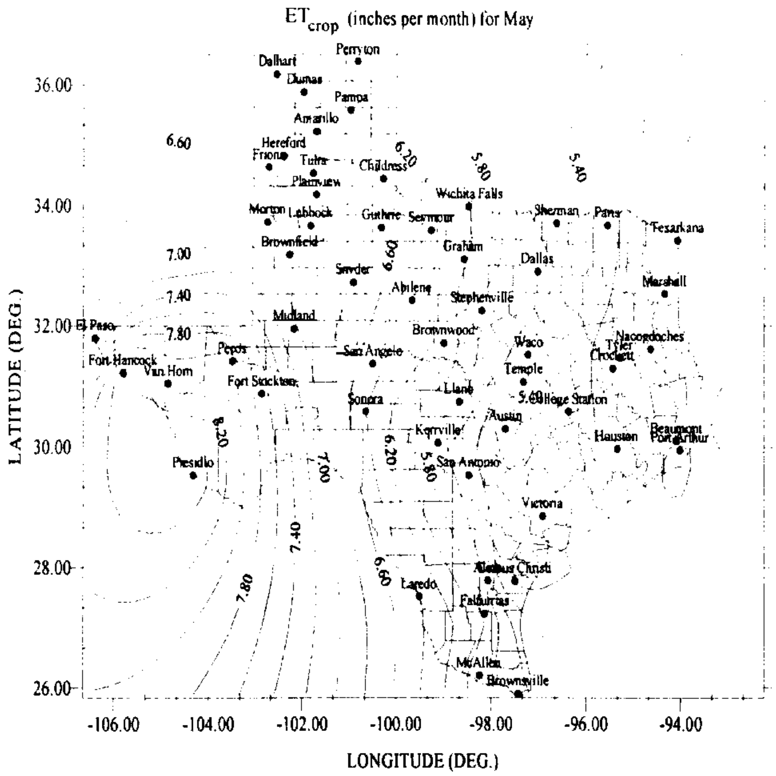


Figure 36.- ET_{crop} for Turfgrass with K_{cb}=0.75 (inches per month).



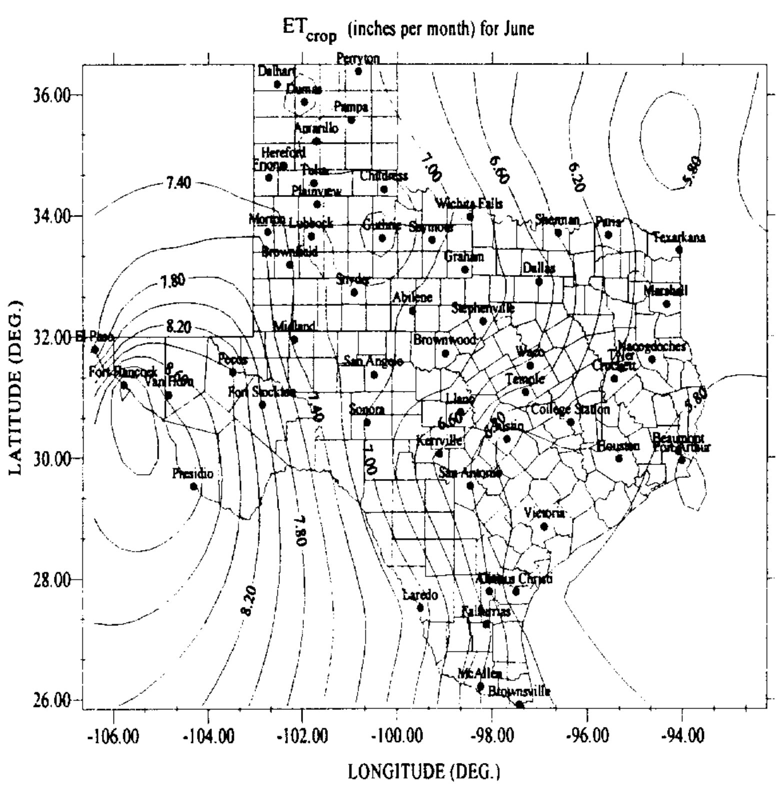
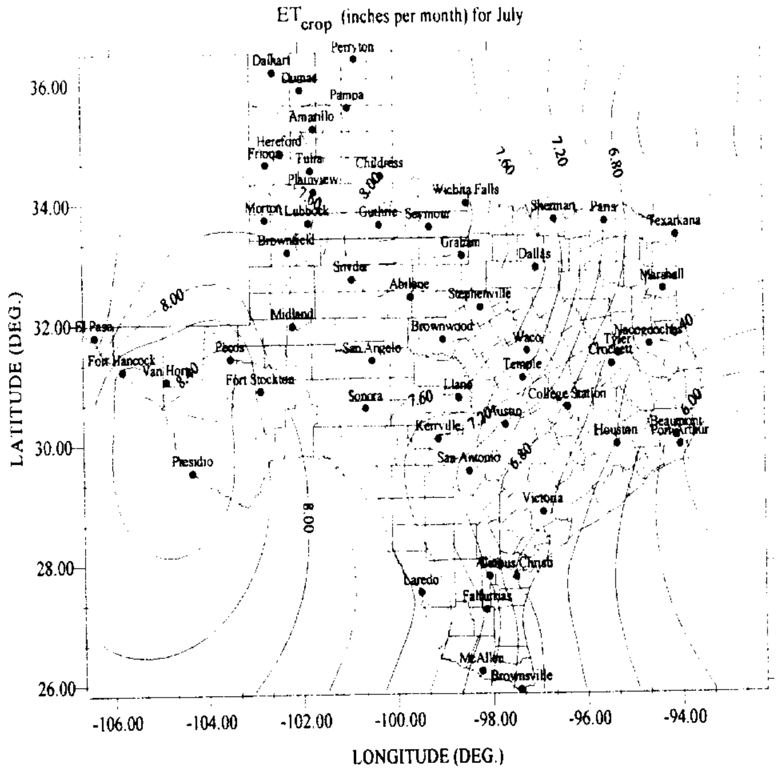


Figure 36.- ET_{crop} for Turfgrass with K_{cb}=0.75 (inches per month).



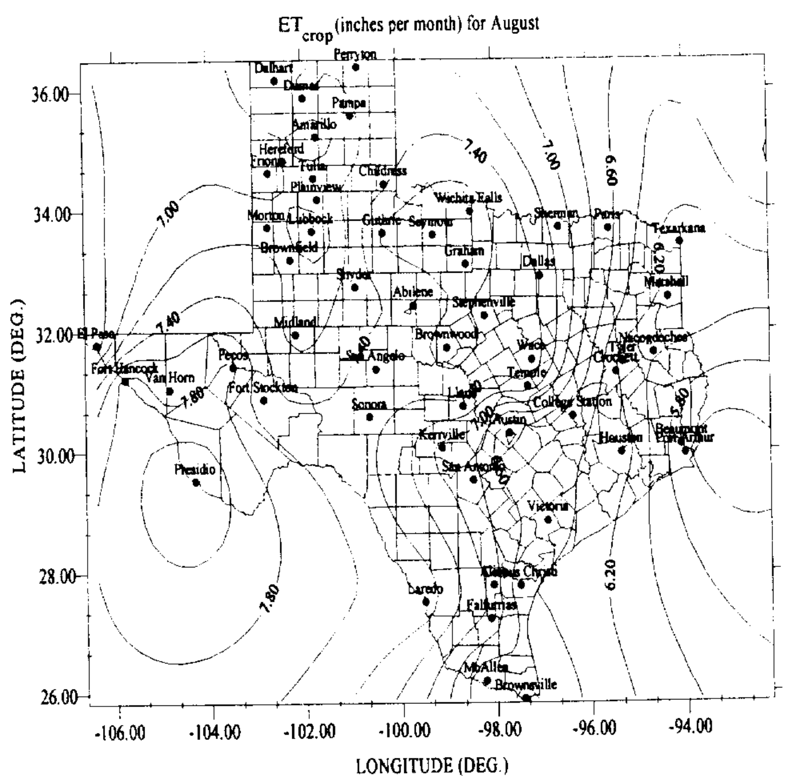
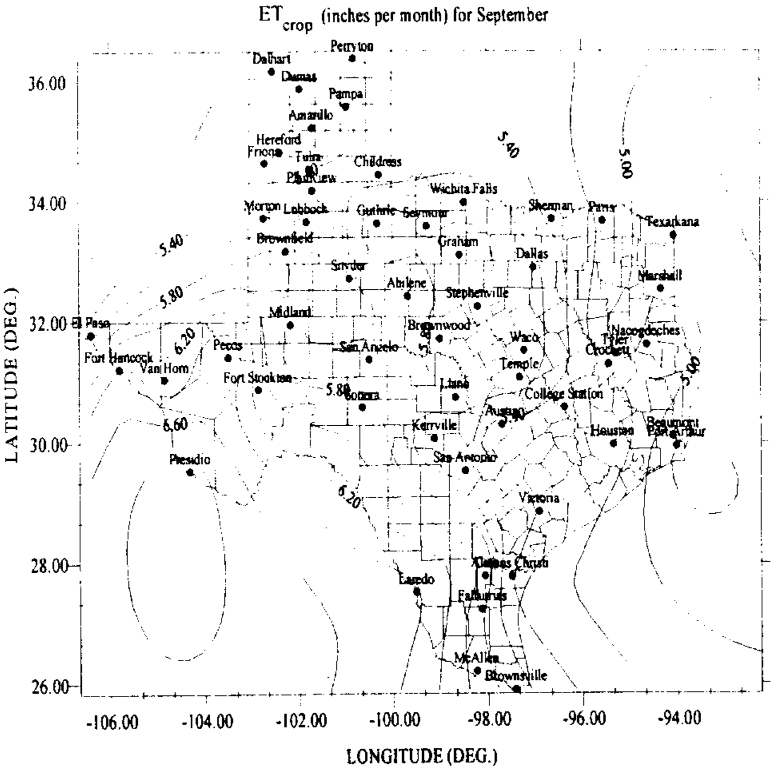


Figure 36.- ET_{crop} for Turfgrass with K_{cb}=0.75 (inches per month).



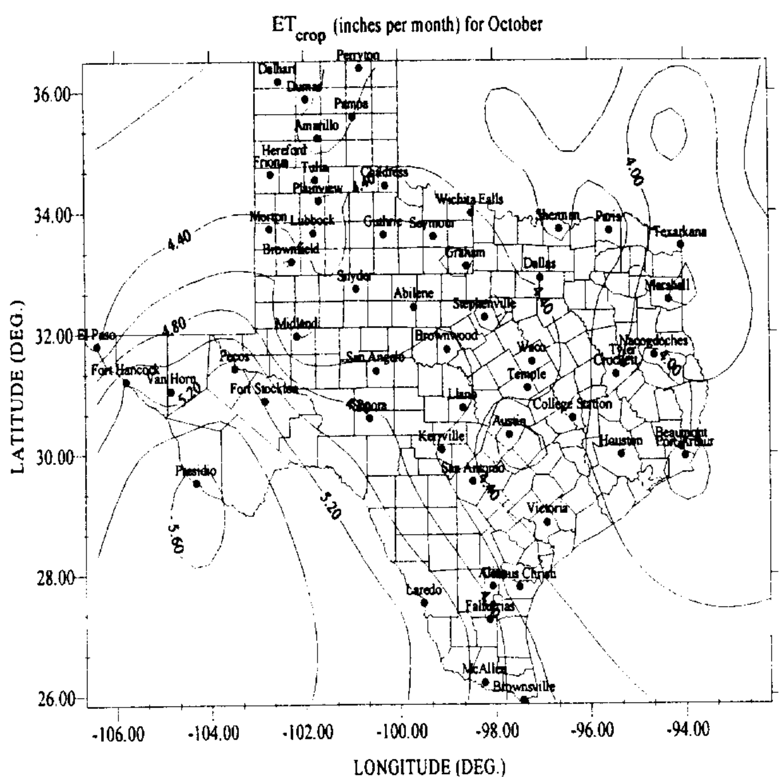
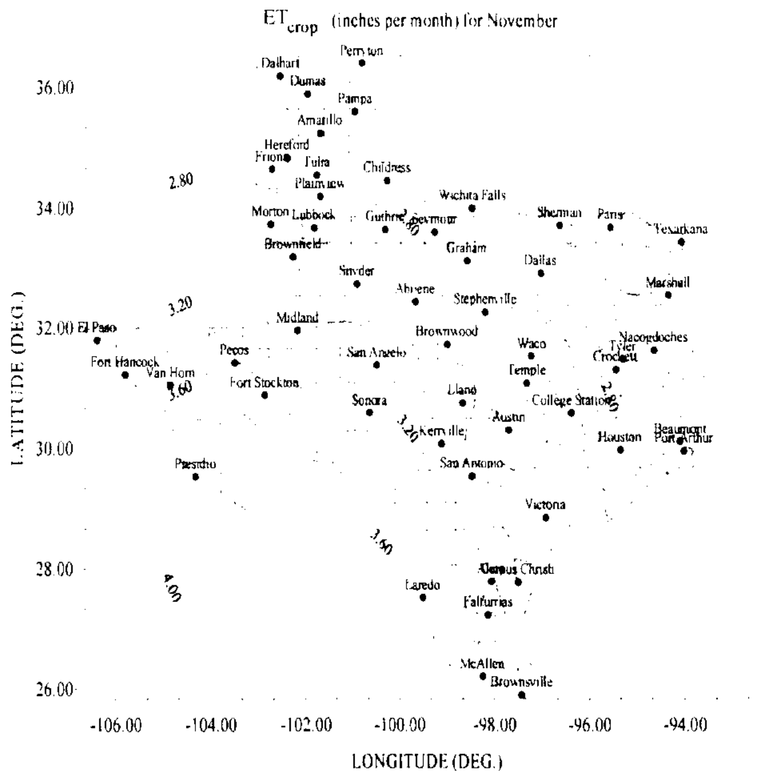


Figure 36.-ET_{crop} for Turfgrass with K_{cb}=0.75 (inches per month).



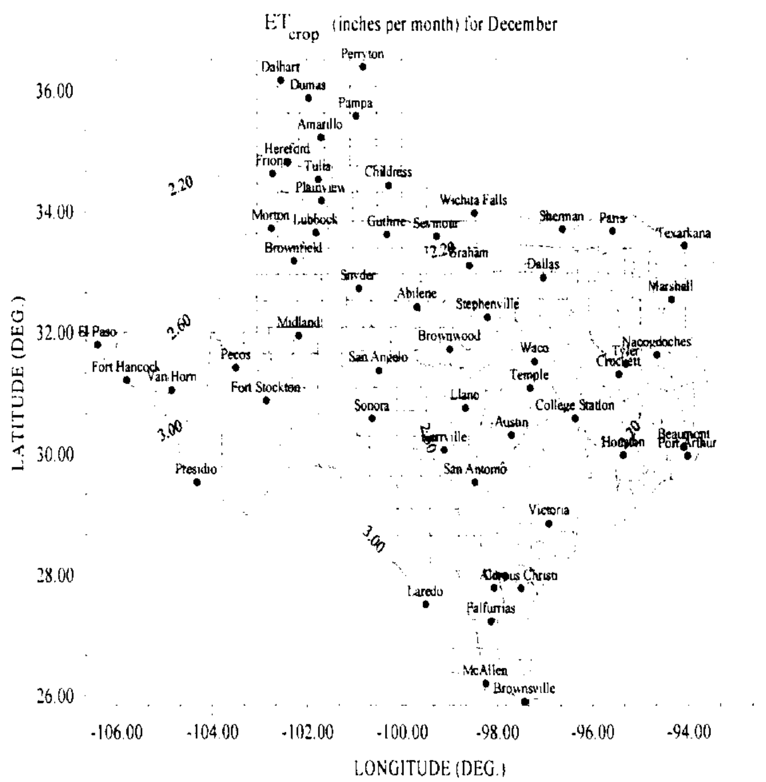


Figure 36.- ET_{crop} for Turfgrass with K_{cb}=0.75 (inches per month).

Table 21.-ET$_{crop}$ for Turfgrass with K_{cb} =1.0 (inches per month).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	2.61	2.83	4.68	6.05	6.91	7.62	8.50	8.14	6.22	4.86	3.31	2.51
Alice	2.99	3.36	4.92	5.52	6.20	6.88	7.80	7.71	6.23	5.28	3.83	3.17
Amarillo	2.36	2.65	4.27	5.70	6.70	7.38	8.08	7.29	5.61	4.47	2.88	2.28
Austin	2.70	2.88	4.31	5.10	5.51	6.42	7.76	7.19	5.87	4.35	2.99	2.48
Beaumont	2.36	2.72	3.93	4.71	5.76	6.18	6.27	6.02	5.16	4.40	3.16	2.41
Brownfield	2.73	3.18	5.11	6.50	7.59	8.14	8.58	7.82	6.11	5.03	3.49	2.88
Brownsville	2.95	3.30	4.78	5.52	6.38	6.83	7.55	7.32	6.01	5.14	3.74	3.07
Brownwood	2.76	3.14	4.88	5.94	6.68	7.61	8.75	8.40	6.33	5.17	3.47	2.83
Childress	2.47	2.80	4.58	5.94	6.96	7.74	8.83	8.06	6.08	4.89	3.10	2.44
College Station	2.52	2.89	4.30	5.00	5.83	6.60	7.46	7.15	5.66	4.58	3.21	2.66
Corpus Christi	2.72	3.02	4.44	5.10	5.77	6.49	7.41	7.19	5.84	4.94	3.50	2.86
Crockett	2.32	2.71	4.12	4.93	5.76	6.40	7.06	6.85	5.54	4.41	3.07	2.47
Dalhart	2.37	2.69	4.37	5.86	6.96	7.80	8.42	7.56	5.75	4.64	2.98	2.31
Dumas	2.26	2.58	4.23	5.77	6.91	7.71	8.59	7.70	5.83	4.65	2.91	2.24
El Paso	2.83	3.54	5.48	6.89	8.37	8.78	8.30	7.46	6.30	4.97	3.58	2.65
Falfurrias	3.02	3.43	4.98	5.65	6.59	7.01	7.93	7.72	6.28	5.35	3.85	3.15
Fort Davis	3.40	3.93	5.86	7.04	8.11	8.45	8.11	7.58	6.36	5.35	4.01	3.33
Fort Hancock	3.44	4.29	6.43	7.97	9.48	10.11	9.30	8.47	6.94	5.77	4.25	3.30
Fort Stockton	3.34	3.88	5.93	7.25	8.20	8.60	8.79	8.22	6.65	5.53	4.09	3.37
Fort Worth	2.50	2.82	4.31	5.38	6.05	7.28	8.56	8.23	6.23	4.72	3.11	2.56
Friona	2.50	2.81	4.58	6.01	7.12	7.92	8.31	7.51	5.84	4.72	3.15	2.50
Graham	2.55	2.91	4.58	5.71	6.46	7.45	8.74	8.35	6.34	5.03	3.34	2.64
Guthrie	2.71	3.00	4.84	6.25	7.20	8.04	9.07	8.34	6.32	5.10	3.45	2.68
Hereford	2.43	2.76	4.49	5.99	7.08	7.84	8.34	7.50	5.81	4.76	3.11	2.44
Houston	2.55	2.72	4.17	5.06	5.94	6.47	6.94	6.88	5.76	4.51	3.12	2.46
Kerrville	2.81	3.13	4.74	5.44	6.04	6.84	7.86	7.68	5.90	4.88	3.47	2.86
Laredo	3.35	3.87	5.65	6.29	7.18	7.79	8.61	8.43	6.82	5.72	4.18	3.43
Llano	2.93	3.22	4.85	5.71	6.34	7.32	8.48	8.14	6.20	5.09	3.57	2.95
Lubbock	2.49	2.92	4.78	6.00	7.05	7.65	7.94	7.33	5.63	4.55	3.15	2.50
Marshall	2.19	2.66	3.99	4.90	5.69	6.25	7.09	6.72	5.32	4.14	2.88	2.28

Table 21.-ET$_{crop}$ for Turfgrass with K$_{cb}$ =1.0 (inches per month) (continued).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
McAllen	3.13	3.58	5.17	5.86	6.57	7.12	8.03	7.06	6.41	5.49	4.00	3.28
Midland	2.92	3.45	5.44	6.65	7.77	8.14	8.39	7.87	6.25	4.83	3.50	2.98
Morton	2.68	3.08	4.92	6.30	7.42	8.12	8.39	7.58	5.92	4.86	3.40	2.71
Nacogdoches	2.19	2.64	4.07	4.89	5.78	6.34	6.86	6.64	5.45	4.21	2.97	2.35
Pampa	2.25	2.52	4.17	5.61	6.61	7.48	8.51	7.67	5.83	4.58	2.86	2.22
Paris	2.09	2.50	3.91	4.99	5.71	6.61	7.63	7.24	5.49	4.69	2.77	2.14
Pecos	3.37	4.05	6.28	7.74	8.92	9.29	9.37	8.63	7.10	5.82	4.21	3.44
Perryton	2.15	2.48	4.02	5.52	6.52	7.55	8.68	7.79	5.89	4.64	2.83	2.14
Plainview	2.49	2.86	4.63	6.05	7.11	7.78	8.36	7.68	5.87	4.83	3.16	2.53
Port Arthur	2.25	2.56	3.84	4.63	5.60	6.05	6.18	6.00	5.12	4.23	2.85	2.24
Presidio	4.04	4.82	7.19	8.49	9.62	9.90	9.42	9.01	7.58	6.37	4.81	3.96
San Angelo	2.99	3.43	5.27	6.38	7.11	7.87	8.73	8.32	6.21	5.13	3.61	2.98
San Antonio	2.79	3.19	4.71	5.42	6.08	6.86	7.82	7.68	6.08	4.89	3.41	2.81
Seymour	2.40	2.81	4.51	5.51	6.69	7.61	8.88	8.40	6.24	4.96	3.14	2.47
Sherman	2.19	2.56	3.99	5.10	5.82	6.80	8.12	7.81	5.77	4.44	2.89	2.23
Snyder	2.70	3.18	5.01	6.35	7.56	7.87	8.67	8.10	6.10	4.91	3.44	2.78
Sonora	3.26	3.72	5.56	6.44	7.06	7.75	8.53	8.18	6.40	5.34	3.81	3.22
Stephenville	2.48	2.81	4.50	5.44	6.15	7.16	8.40	8.09	6.22	4.70	3.31	2.58
Temple	2.51	2.83	4.36	5.24	5.96	7.00	8.18	8.11	6.12	4.97	3.30	2.60
Texarkana	2.12	2.67	3.97	4.96	5.70	6.31	7.02	6.72	5.28	4.06	2.90	2.16
Tulia	2.49	2.81	4.54	5.98	7.05	7.73	8.37	7.61	5.84	4.80	3.14	2.46
Tyler	2.16	2.59	3.98	4.88	5.68	6.42	7.16	6.77	5.41	4.31	2.94	2.35
Uvalde	4.30	4.03	4.81	4.82	5.41	6.01	7.16	7.47	6.68	6.20	5.24	4.76
Van Horn	3.27	3.99	6.08	7.60	8.99	9.46	8.94	8.20	6.75	5.63	4.04	3.21
Victoria	2.65	2.97	4.44	5.13	5.86	6.55	7.36	7.20	5.80	4.83	3.38	2.76
Waco	2.47	2.82	4.35	5.18	6.05	7.23	8.50	8.43	6.32	5.03	3.26	2.55
Wichita Falls	2.33	2.67	4.35	5.48	6.50	7.63	8.96	8.47	6.22	4.83	3.03	2.34

Table 22.- ET_{crop} for Turfgrass with K_{cb}=0.90 (inches per month).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	2.53	2.76	4.61	5.95	6.77	7.46	8.34	7.99	6.09	4.76	3.21	2.43
Alice	2.85	3.22	4.74	5.31	5.99	6.66	7.55	7.47	6.12	5.11	3.66	3.02
Amarillo	2.32	2.61	4.25	5.67	6.63	7.31	7.99	7.21	5.53	4.42	2.83	2.23
Austin	2.60	2.79	4.23	4.97	5.38	6.26	7.55	6.97	5.72	4.26	2.90	2.39
Beaumont	2.29	2.62	3.85	4.56	5.59	6.02	6.17	5.90	5.06	4.29	3.04	2.33
Brownfield	2.68	3.12	5.05	6.44	7.48	8.03	8.44	7.70	6.04	4.95	3.42	2.82
Brownsville	2.83	3.14	4.58	5.29	6.13	6.59	7.29	7.11	5.90	5.00	3.56	2.92
Brownwood	2.68	3.07	4.79	5.86	6.55	7.44	8.58	8.26	6.22	5.07	3.36	2.74
Childress	2.41	2.75	4.54	5.88	6.86	7.65	8.69	7.94	5.96	4.81	3.03	2.39
College Station	2.45	2.80	4.23	4.90	5.70	6.44	7.26	6.97	5.55	4.49	3.12	2.58
Corpus Christi	2.60	2.88	4.26	4.89	5.54	6.25	7.13	6.94	5.71	4.78	3.33	2.72
Crockett	2.27	2.64	4.07	4.84	5.64	6.25	6.90	6.68	5.43	4.31	2.99	2.41
Dalhart	2.33	2.65	4.35	5.84	6.92	7.73	8.36	7.48	5.67	4.60	2.94	2.27
Dallas	2.47	2.79	4.29	5.36	6.01	7.20	8.44	8.08	6.13	4.69	3.07	2.52
Dumas	2.23	2.56	4.12	5.63	6.77	7.59	8.53	7.64	5.77	4.61	2.87	2.19
El Paso	2.68	3.36	5.26	6.57	7.91	8.37	8.02	7.21	6.05	4.78	3.39	2.51
Falfurrias	2.97	3.40	4.97	5.50	6.59	7.00	7.84	7.61	6.20	5.29	3.79	3.08
Fort Hancock	3.30	4.15	6.29	7.81	9.25	9.88	9.09	8.33	6.79	5.64	4.08	3.16
Fort Stockton	3.26	3.79	5.85	7.14	8.08	8.43	8.65	8.04	6.51	5.44	3.99	3.28
Friona	2.46	2.77	4.55	5.98	7.05	7.82	8.18	7.40	5.76	4.66	3.10	2.45
Graham	2.49	2.84	4.52	5.64	6.36	7.31	8.60	8.21	6.24	4.95	3.25	2.57
Guthrie	2.64	2.95	4.79	6.19	7.11	7.94	8.95	8.21	6.23	5.00	3.35	2.62
Hereford	2.39	2.72	4.46	5.97	7.02	7.77	8.24	7.42	5.73	4.70	3.06	2.39
Houston	2.48	2.63	4.08	4.92	5.77	6.32	6.77	6.71	5.61	4.40	3.02	2.38
Kerrville	2.74	3.06	4.68	5.34	5.93	6.71	7.69	7.50	5.78	4.80	3.39	2.79
Laredo	3.22	3.74	5.46	6.12	6.95	7.59	8.32	8.18	6.70	5.56	4.03	3.32
Llano	2.84	3.14	4.77	5.61	6.21	7.16	8.29	7.97	6.08	4.99	3.46	2.86
Lubbock	2.42	2.86	4.73	5.93	6.94	7.54	7.81	7.19	5.51	4.47	3.07	2.44
Marshall	2.16	2.60	3.95	4.84	5.57	6.12	6.93	6.57	5.21	4.04	2.80	2.23

Table 22.- ET_{crop} for Turfgrass with K_{cb}=0.90 (inches per month) (cont'd).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
McAllen	2.99	3.43	4.97	5.64	6.34	6.88	7.74	6.85	6.25	5.32	3.81	3.13
Midland	2.85	3.38	5.39	6.59	7.66	8.00	8.26	7.73	6.12	4.74	3.41	2.91
Morton	2.62	3.03	4.88	6.26	7.36	8.05	8.29	7.50	5.82	4.79	3.33	2.67
Nacogdoches	2.14	2.59	4.01	4.79	5.67	6.22	6.74	6.46	5.32	4.16	2.88	2.30
Pampa	2.21	2.48	4.14	5.58	6.55	7.42	8.40	7.58	5.76	4.53	2.82	2.17
Paris	2.03	2.44	3.86	4.93	5.64	6.49	7.47	7.09	5.41	4.62	2.69	2.09
Pecos	3.29	3.98	6.24	7.69	8.84	9.19	9.23	8.49	6.99	5.73	4.12	3.36
Perryton	2.11	2.43	3.99	5.48	6.45	7.47	8.58	7.69	5.80	4.58	2.78	2.09
Plainview	2.44	2.82	4.59	6.00	7.05	7.72	8.23	7.59	5.78	4.77	3.09	2.48
Port Arthur	2.18	2.46	3.74	4.47	5.43	5.86	6.05	5.87	5.01	4.11	2.75	2.16
Presidio	3.93	4.72	7.11	8.41	9.50	9.78	9.29	8.86	7.43	6.24	4.69	3.84
San Angelo	2.90	3.35	5.19	6.29	6.98	7.71	8.56	8.17	6.07	5.01	3.49	2.89
San Antonio	2.70	3.10	4.61	5.30	5.91	6.68	7.57	7.47	5.93	4.78	3.30	2.71
Seymour	2.34	2.74	4.46	5.45	6.59	7.49	8.75	8.29	6.14	4.88	3.06	2.41
Sherman	2.12	2.49	3.94	5.04	5.73	6.69	7.95	7.65	5.66	4.36	2.81	2.16
Snyder	2.64	3.11	4.94	6.27	7.43	7.73	8.51	7.93	5.97	4.82	3.35	2.70
Sonora	3.16	3.62	5.46	6.34	6.92	7.58	8.38	8.04	6.26	5.23	3.69	3.11
Stephenville	2.39	2.74	4.41	5.34	6.04	7.08	8.25	7.98	6.11	4.61	3.19	2.50
Temple	2.44	2.76	4.27	5.15	5.83	6.82	7.99	7.94	6.02	4.86	3.20	2.53
Texarkana	2.06	2.61	3.92	4.89	5.59	6.17	6.86	6.53	5.15	4.00	2.82	2.10
Tulia	2.44	2.77	4.51	5.94	6.98	7.65	8.27	7.52	5.76	4.73	3.08	2.42
Tyler	2.11	2.52	3.93	4.82	5.57	6.28	6.98	6.58	5.29	4.21	2.85	2.28
Van Horn	3.20	3.93	6.05	7.58	8.94	9.41	8.86	8.12	6.67	5.55	3.97	3.14
Victoria	2.55	2.85	4.30	4.95	5.66	6.36	7.13	6.99	5.67	4.70	3.24	2.64
Waco	2.38	2.73	4.27	5.08	5.91	7.08	8.29	8.26	6.18	4.93	3.17	2.47
Wichita Falls	2.26	2.61	4.30	5.42	6.40	7.48	8.80	8.34	6.11	4.74	2.95	2.27

Table 23.- ET_{crop} for Turfgrass with K_{cb}=0.85 (inches per month).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	2.43	2.66	4.49	5.81	6.60	7.28	8.11	7.78	5.95	4.65	3.09	2.33
Alice	2.75	3.10	4.58	5.15	5.85	6.51	7.36	7.29	6.05	4.98	3.53	2.91
Amarillo	2.23	2.50	4.13	5.52	6.47	7.18	7.82	7.08	5.39	4.30	2.72	2.14
Austin	2.51	2.70	4.14	4.85	5.27	6.12	7.34	6.76	5.60	4.18	2.81	2.31
Beaumont	2.25	2.55	3.79	4.46	5.47	5.92	6.11	5.83	4.99	4.21	2.95	2.28
Brownfield	2.59	3.00	4.89	6.24	7.27	7.83	8.21	7.52	5.94	4.84	3.29	2.71
Brownsville	2.75	3.02	4.43	5.14	5.97	6.44	7.10	6.96	5.83	4.90	3.44	2.82
Brownwood	2.58	2.97	4.66	5.76	6.43	7.27	8.36	8.08	6.10	4.95	3.24	2.65
Childress	2.32	2.66	4.42	5.75	6.71	7.52	8.46	7.75	5.81	4.69	2.92	2.30
College Station	2.39	2.73	4.16	4.81	5.60	6.32	7.09	6.81	5.46	4.41	3.04	2.52
Corpus Christi	2.51	2.77	4.13	4.75	5.41	6.10	6.94	6.76	5.62	4.67	3.21	2.62
Crockett	2.22	2.58	4.01	4.76	5.55	6.14	6.77	6.54	5.34	4.23	2.92	2.35
Dalhart	2.24	2.54	4.24	5.70	6.78	7.59	8.23	7.36	5.54	4.48	2.82	2.18
Dallas	2.39	2.71	4.21	5.26	5.91	7.05	8.20	7.85	5.97	4.59	2.98	2.43
Dumas	2.14	2.47	4.12	5.63	6.77	7.59	8.36	7.50	5.64	4.49	2.77	2.11
El Paso	2.56	3.21	5.08	6.33	7.62	8.08	7.81	7.02	5.88	4.63	3.24	2.40
Falfurrias	2.86	3.29	4.81	5.50	6.41	6.83	7.63	7.39	6.08	5.16	3.64	2.96
Fort Hancock	3.17	3.99	6.11	7.62	9.04	9.70	8.91	8.20	6.65	5.50	3.92	3.04
Fort Stockton	3.18	3.69	5.77	7.04	7.95	8.28	8.48	7.84	6.38	5.35	3.89	3.19
Friona	2.35	2.66	4.40	5.80	6.86	7.60	7.94	7.22	5.63	4.54	2.97	2.34
Graham	2.40	2.75	4.43	5.53	6.25	7.15	8.40	8.03	6.12	4.86	3.15	2.49
Guthrie	2.53	2.87	4.67	6.08	6.98	7.82	8.76	8.03	6.13	4.88	3.22	2.52
Hereford	2.29	2.62	4.34	5.81	6.86	7.63	8.07	7.29	5.60	4.58	2.94	2.30
Houston	2.42	2.55	4.01	4.81	5.65	6.21	6.65	6.58	5.51	4.32	2.94	2.31
Kerrville	2.66	2.97	4.60	5.24	5.83	6.58	7.50	7.30	5.68	4.72	3.29	2.71
Laredo	3.11	3.61	5.28	5.97	6.77	7.43	8.08	7.97	6.60	5.42	3.90	3.22
Llano	2.74	3.04	4.66	5.50	6.10	7.01	8.06	7.77	5.96	4.88	3.35	2.76
Lubbock	2.32	2.74	4.60	5.76	6.77	7.37	7.63	7.02	5.38	4.35	2.94	2.34
Marshall	2.12	2.54	3.91	4.78	5.48	6.02	6.81	6.43	5.13	3.96	2.74	2.18

Table 23.- ET_{crop} for Turfgrass with K_{cb}=0.85 (inches per month) (cont'd).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
McAllen	2.89	3.31	4.81	5.49	6.19	6.71	7.52	6.70	6.14	5.19	3.66	3.02
Midland	2.73	3.24	5.22	6.40	7.44	7.78	8.03	7.53	5.97	4.60	3.27	2.78
Morton	2.53	2.93	4.74	6.12	7.20	7.90	8.12	7.39	5.68	4.67	3.21	2.57
Nacogdoches	2.09	2.54	3.96	4.70	5.58	6.13	6.64	6.31	5.23	4.12	2.81	2.25
Pampa	2.12	2.39	4.03	5.46	6.45	7.31	8.22	7.45	5.65	4.42	2.71	2.09
Paris	1.98	2.37	3.81	4.87	5.57	6.38	7.31	6.95	5.33	4.54	2.62	2.04
Pecos	3.16	3.82	6.04	7.46	8.59	8.93	8.99	8.28	6.84	5.58	3.95	3.23
Perryton	2.03	2.34	3.90	5.35	6.33	7.34	8.40	7.54	5.67	4.45	2.68	2.01
Plainview	2.34	2.73	4.47	5.87	6.93	7.63	8.04	7.46	5.68	4.66	2.97	2.39
Port Arthur	2.13	2.39	3.67	4.36	5.32	5.74	5.97	5.79	4.94	4.02	2.67	2.10
Presidio	3.75	4.52	6.86	8.12	9.19	9.48	9.06	8.64	7.23	6.05	4.48	3.66
San Angelo	2.78	3.22	5.04	6.13	6.81	7.51	8.30	7.95	5.93	4.89	3.36	2.77
San Antonio	2.61	2.99	4.49	5.17	5.78	6.52	7.35	7.27	5.80	4.68	3.19	2.61
Seymour	2.26	2.65	4.37	5.34	6.47	7.34	8.55	8.11	6.02	4.79	2.95	2.33
Sherman	2.05	2.42	3.88	4.98	5.64	6.58	7.77	7.47	5.56	4.28	2.73	2.10
Snyder	2.53	2.99	4.79	6.10	7.24	7.53	8.27	7.72	5.84	4.70	3.21	2.59
Sonora	3.03	3.48	5.29	6.18	6.74	7.38	8.16	7.84	6.13	5.10	3.55	2.98
Stephenville	2.29	2.64	4.30	5.22	5.94	6.99	8.05	7.84	6.00	4.50	3.07	2.41
Temple	2.38	2.70	4.18	5.07	5.73	6.66	7.77	7.75	5.92	4.75	3.11	2.46
Texarkana	2.02	2.54	3.86	4.82	5.49	6.06	6.73	6.37	5.05	3.93	2.76	2.04
Tulia	2.34	2.67	4.39	5.81	6.84	7.53	8.09	7.39	5.65	4.62	2.96	2.32
Tyler	2.06	2.46	3.88	4.76	5.48	6.17	6.82	6.42	5.19	4.12	2.78	2.23
Van Horn	3.07	3.77	5.86	7.35	8.67	9.18	8.69	7.97	6.54	5.39	3.82	3.01
Victoria	2.47	2.76	4.19	4.82	5.53	6.23	6.97	6.85	5.57	4.59	3.13	2.55
Waco	2.30	2.64	4.17	4.97	5.78	6.92	8.04	8.03	6.04	4.82	3.07	2.38
Wichita Falls	2.17	2.52	4.20	5.31	6.27	7.31	8.55	8.14	5.98	4.64	2.84	2.19

Table 24.-ET_{crop} for Turfgrass with K_{cb}=0.80 (inches per month).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	2.33	2.55	4.36	5.66	6.43	7.09	7.89	7.57	5.81	4.54	2.97	2.24
Alice	2.65	2.99	4.43	5.00	5.71	6.37	7.18	7.11	5.98	4.85	3.39	2.79
Amarillo	2.13	2.40	4.01	5.37	6.31	7.05	7.64	6.94	5.24	4.18	2.61	2.04
Austin	2.43	2.61	4.06	4.74	5.17	5.99	7.14	6.54	5.47	4.10	2.72	2.22
Beaumont	2.20	2.48	3.73	4.36	5.36	5.82	6.05	5.75	4.93	4.12	2.86	2.22
Brownfield	2.50	2.87	4.72	6.05	7.06	7.64	7.98	7.34	5.85	4.73	3.17	2.60
Brownsville	2.67	2.91	4.29	4.99	5.81	6.29	6.91	6.81	5.76	4.80	3.32	2.71
Brownwood	2.49	2.88	4.54	5.65	6.30	7.09	8.14	7.90	5.99	4.83	3.12	2.55
Childress	2.22	2.57	4.30	5.61	6.57	7.39	8.23	7.55	5.66	4.57	2.80	2.20
College Station	2.34	2.65	4.09	4.73	5.50	6.20	6.92	6.65	5.36	4.33	2.96	2.45
Corpus Christi	2.42	2.67	3.99	4.60	5.27	5.95	6.74	6.59	5.52	4.56	3.08	2.51
Crockett	2.18	2.52	3.96	4.68	5.46	6.03	6.64	6.39	5.25	4.15	2.85	2.30
Dalhart	2.14	2.43	4.12	5.56	6.65	7.45	8.11	7.24	5.42	4.36	2.71	2.09
Dallas	2.31	2.62	4.13	5.15	5.80	6.90	7.96	7.62	5.81	4.49	2.88	2.35
Dumas	2.05	2.38	4.12	5.63	6.77	7.59	8.19	7.36	5.51	4.36	2.66	2.02
El Paso	2.44	3.07	4.90	6.10	7.32	7.80	7.60	6.82	5.71	4.49	3.09	2.30
Falfurrias	2.76	3.17	4.66	5.50	6.24	6.66	7.42	7.18	5.96	5.03	3.50	2.84
Fort Hancock	3.04	3.84	5.94	7.43	8.84	9.51	8.73	8.07	6.52	5.36	3.76	2.92
Fort Stockton	3.10	3.60	5.68	6.94	7.81	8.13	8.32	7.64	6.25	5.27	3.80	3.11
Friona	2.25	2.55	4.25	5.62	6.66	7.38	7.70	7.04	5.50	4.42	2.85	2.24
Graham	2.32	2.67	4.33	5.43	6.14	7.00	8.19	7.84	6.01	4.76	3.04	2.40
Guthrie	2.42	2.78	4.55	5.97	6.85	7.70	8.56	7.85	6.03	4.75	3.08	2.42
Hereford	2.19	2.52	4.21	5.66	6.70	7.49	7.89	7.17	5.47	4.45	2.83	2.21
Houston	2.36	2.47	3.93	4.71	5.53	6.10	6.53	6.46	5.41	4.23	2.86	2.24
Kerrville	2.59	2.88	4.52	5.14	5.73	6.45	7.32	7.10	5.58	4.64	3.20	2.63
Laredo	3.00	3.48	5.09	5.81	6.59	7.27	7.83	7.75	6.51	5.28	3.77	3.13
Llano	2.64	2.94	4.55	5.39	5.98	6.85	7.84	7.58	5.85	4.78	3.23	2.66
Lubbock	2.21	2.63	4.46	5.60	6.60	7.19	7.45	6.85	5.25	4.24	2.82	2.24
Marshall	2.09	2.48	3.87	4.73	5.39	5.93	6.68	6.30	5.05	3.87	2.67	2.14

Table 24.- ET_{crop} for Turfgrass with K_{cb}=0.80 (inches per month).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
McAllen	2.80	3.19	4.65	5.33	6.03	6.55	7.31	6.54	6.04	5.06	3.52	2.91
Midland	2.60	3.10	5.05	6.20	7.22	7.55	7.79	7.32	5.81	4.47	3.12	2.66
Morton	2.43	2.82	4.60	5.97	7.04	7.75	7.95	7.27	5.55	4.55	3.08	2.48
Nacogdoches	2.05	2.48	3.91	4.61	5.49	6.04	6.54	6.17	5.13	4.08	2.74	2.21
Pampa	2.03	2.30	3.93	5.34	6.35	7.21	8.03	7.32	5.54	4.31	2.61	2.00
Paris	1.92	2.31	3.76	4.81	5.50	6.27	7.16	6.80	5.25	4.47	2.54	1.98
Pecos	3.03	3.66	5.84	7.22	8.34	8.68	8.74	8.06	6.69	5.44	3.78	3.09
Perryton	1.95	2.25	3.80	5.22	6.21	7.21	8.23	7.38	5.53	4.32	2.58	1.93
Plainview	2.25	2.63	4.35	5.73	6.81	7.53	7.84	7.33	5.58	4.56	2.85	2.31
Port Arthur	2.08	2.32	3.59	4.26	5.21	5.63	5.89	5.71	4.87	3.94	2.59	2.05
Presidio	3.57	4.31	6.61	7.82	8.87	9.19	8.83	8.42	7.04	5.86	4.28	3.49
San Angelo	2.66	3.09	4.89	5.96	6.65	7.31	8.05	7.73	5.80	4.76	3.22	2.65
San Antonio	2.51	2.89	4.38	5.05	5.65	6.37	7.13	7.08	5.67	4.58	3.08	2.52
Seymour	2.17	2.56	4.27	5.23	6.36	7.20	8.35	7.94	5.89	4.69	2.84	2.25
Sherman	1.98	2.35	3.83	4.92	5.56	6.48	7.58	7.30	5.46	4.21	2.65	2.03
Snyder	2.42	2.87	4.64	5.93	7.04	7.34	8.02	7.51	5.70	4.59	3.08	2.48
Sonora	2.91	3.34	5.12	6.03	6.57	7.17	7.94	7.65	6.00	4.98	3.41	2.85
Stephenville	2.20	2.55	4.18	5.10	5.84	6.91	7.86	7.70	5.89	4.40	2.94	2.32
Temple	2.31	2.63	4.09	4.98	5.62	6.50	7.56	7.55	5.82	4.64	3.01	2.39
Texarkana	1.97	2.48	3.80	4.75	5.40	5.95	6.60	6.21	4.95	3.87	2.69	1.99
Tulia	2.25	2.57	4.27	5.68	6.70	7.41	7.91	7.26	5.53	4.51	2.85	2.23
Tyler	2.02	2.40	3.83	4.70	5.40	6.05	6.67	6.25	5.09	4.03	2.71	2.18
Van Horn	2.95	3.61	5.68	7.12	8.39	8.95	8.53	7.82	6.41	5.24	3.67	2.89
Victoria	2.39	2.66	4.08	4.69	5.40	6.10	6.81	6.70	5.48	4.49	3.02	2.46
Waco	2.22	2.55	4.07	4.87	5.65	6.77	7.79	7.80	5.89	4.72	2.97	2.30
Wichita Falls	2.08	2.43	4.10	5.20	6.15	7.14	8.30	7.93	5.85	4.53	2.73	2.10

Table 25.-ET$_{crop}$ for Turfgrass with K_{cb}=0.75 (inches per month).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	2.23	2.45	4.24	5.52	6.27	6.90	7.67	7.37	5.67	4.43	2.85	2.14
Alice	2.55	2.87	4.28	4.84	5.57	6.22	6.99	6.93	5.90	4.72	3.25	2.68
Amarillo	2.03	2.29	3.89	5.22	6.14	6.92	7.46	6.81	5.10	4.07	2.50	1.95
Austin	2.34	2.52	3.97	4.62	5.07	5.86	6.94	6.33	5.34	4.02	2.63	2.14
Beaumont	2.15	2.40	3.67	4.26	5.25	5.72	5.99	5.67	4.86	4.04	2.77	2.16
Brownfield	2.40	2.75	4.56	5.86	6.85	7.45	7.75	7.16	5.75	4.62	3.05	2.50
Brownsville	2.58	2.80	4.14	4.84	5.65	6.14	6.73	6.66	5.69	4.70	3.20	2.61
Brownwood	2.39	2.79	4.41	5.55	6.17	6.92	7.92	7.71	5.87	4.72	3.00	2.46
Childress	2.12	2.48	4.17	5.48	6.42	7.26	8.00	7.36	5.51	4.45	2.69	2.11
College Station	2.28	2.58	4.02	4.64	5.40	6.08	6.75	6.49	5.27	4.25	2.88	2.39
Corpus Christi	2.32	2.56	3.86	4.46	5.14	5.80	6.55	6.42	5.43	4.45	2.96	2.41
Crockett	2.13	2.46	3.91	4.60	5.36	5.92	6.51	6.25	5.16	4.07	2.77	2.25
Dalhart	2.05	2.33	4.00	5.42	6.51	7.31	7.99	7.12	5.29	4.24	2.60	2.00
Dallas	2.23	2.54	4.04	5.04	5.70	6.75	7.72	7.38	5.65	4.39	2.79	2.26
Dumas	1.97	2.29	4.12	5.63	6.77	7.59	8.02	7.23	5.38	4.24	2.56	1.94
El Paso	2.33	2.92	4.72	5.86	7.02	7.52	7.39	6.63	5.54	4.35	2.94	2.19
Falfurrias	2.66	3.06	4.50	5.50	6.07	6.49	7.22	6.97	5.83	4.89	3.36	2.71
Fort Hancock	2.91	3.69	5.76	7.24	8.63	9.32	8.55	7.94	6.39	5.22	3.59	2.80
Fort Stockton	3.02	3.51	5.60	6.83	7.68	7.98	8.15	7.44	6.12	5.18	3.70	3.02
Friona	2.15	2.44	4.10	5.44	6.47	7.17	7.46	6.86	5.38	4.30	2.72	2.13
Graham	2.23	2.58	4.24	5.33	6.03	6.84	7.99	7.65	5.90	4.67	2.94	2.32
Guthrie	2.32	2.70	4.43	5.86	6.72	7.57	8.37	7.66	5.93	4.62	2.95	2.33
Hereford	2.09	2.42	4.09	5.51	6.54	7.36	7.72	7.04	5.34	4.33	2.71	2.11
Houston	2.31	2.39	3.86	4.60	5.40	6.00	6.40	6.33	5.31	4.15	2.78	2.17
Kerrville	2.51	2.79	4.44	5.04	5.63	6.33	7.13	6.90	5.48	4.56	3.11	2.55
Laredo	2.88	3.35	4.90	5.66	6.41	7.12	7.58	7.53	6.42	5.14	3.64	3.03
Llano	2.55	2.84	4.44	5.27	5.87	6.70	7.61	7.38	5.73	4.67	3.12	2.57
Lubbock	2.11	2.52	4.33	5.43	6.42	7.02	7.26	6.67	5.13	4.12	2.69	2.15
Marshall	2.06	2.42	3.84	4.67	5.30	5.83	6.55	6.17	4.97	3.79	2.61	2.10

Table 25.- ET_{crop} for Turfgrass with K_{cb}=0.75 (inches per month) (cont'd).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
McAllen	2.70	3.07	4.49	5.18	5.88	6.38	7.10	6.38	5.93	4.93	3.37	2.80
Midland	2.48	2.96	4.88	6.00	7.00	7.32	7.55	7.11	5.66	4.34	2.98	2.54
Morton	2.33	2.71	4.45	5.82	6.89	7.61	7.78	7.16	5.41	4.43	2.96	2.38
Nacogdoches	2.00	2.43	3.86	4.52	5.40	5.95	6.44	6.02	5.04	4.04	2.67	2.17
Pampa	1.95	2.22	3.83	5.22	6.24	7.10	7.85	7.18	5.43	4.20	2.51	1.92
Paris	1.87	2.25	3.71	4.74	5.43	6.17	7.00	6.66	5.17	4.40	2.47	1.93
Pecos	2.89	3.50	5.64	6.98	8.09	8.42	8.50	7.85	6.54	5.29	3.62	2.95
Perryton	1.86	2.16	3.71	5.09	6.09	7.08	8.05	7.23	5.39	4.19	2.48	1.85
Plainview	2.15	2.54	4.23	5.60	6.68	7.44	7.65	7.19	5.47	4.45	2.73	2.22
Port Arthur	2.03	2.25	3.52	4.15	5.10	5.51	5.81	5.62	4.80	3.85	2.52	1.99
Presidio	3.39	4.10	6.36	7.53	8.55	8.90	8.60	8.20	6.85	5.67	4.07	3.31
San Angelo	2.54	2.96	4.74	5.79	6.48	7.11	7.79	7.51	5.66	4.63	3.08	2.53
San Antonio	2.42	2.78	4.26	4.93	5.51	6.22	6.91	6.88	5.54	4.47	2.96	2.42
Seymour	2.08	2.47	4.18	5.12	6.24	7.05	8.15	7.77	5.77	4.59	2.73	2.16
Sherman	1.92	2.28	3.77	4.85	5.47	6.38	7.40	7.12	5.36	4.13	2.57	1.97
Snyder	2.32	2.75	4.49	5.76	6.85	7.15	7.78	7.30	5.57	4.47	2.95	2.37
Sonora	2.78	3.21	4.94	5.87	6.40	6.97	7.72	7.45	5.87	4.86	3.26	2.71
Stephenville	2.10	2.46	4.06	4.98	5.73	6.82	7.66	7.56	5.78	4.29	2.81	2.24
Temple	2.25	2.57	3.99	4.90	5.52	6.34	7.35	7.36	5.72	4.53	2.92	2.32
Texarkana	1.92	2.41	3.75	4.68	5.31	5.84	6.47	6.04	4.85	3.81	2.62	1.94
Tulia	2.15	2.47	4.15	5.54	6.57	7.29	7.73	7.13	5.42	4.39	2.73	2.14
Tyler	1.97	2.34	3.78	4.64	5.31	5.94	6.51	6.09	4.99	3.95	2.64	2.13
Van Horn	2.82	3.45	5.49	6.88	8.12	8.72	8.36	7.67	6.29	5.08	3.51	2.76
Victoria	2.31	2.57	3.97	4.56	5.27	5.97	6.65	6.55	5.39	4.39	2.92	2.37
Waco	2.14	2.46	3.97	4.76	5.53	6.61	7.54	7.58	5.75	4.61	2.87	2.21
Wichita Falls	1.99	2.33	3.99	5.10	6.03	6.97	8.05	7.73	5.72	4.42	2.62	2.01

Chapter 5

Free-Water Evaporation for Shallow Ponds

Information on free-water evaporation is needed for two types of conditions—for small shallow ponds (wastewater storage ponds, fish ponds, stock ponds, etc.) and for large storage reservoirs. The primary difference between the two types of storage systems is that the heat storage in small ponds is minimal while significant heat storage in large reservoirs causes a time shift on when evaporation occurs. Shallow ponds have been defined as ponds with less than 17 ft depth (Doorenbos and Pruitt, 1977), but there is no definitive criteria in the literature.

The primary source of energy for evaporation is solar radiation (Knapp, 1985; Sacks et al., 1994). However, to some degree the rate and time at which evaporation occurs is controlled by the difference in vapor pressure between the water surface and the atmosphere—the drying power of air. Along with vapor pressure difference, the drying power of air is a function of wind run. Thus it is not surprising that Penman-type equations appear to be best at estimating free-water evaporation (Calder and Neal, 1984; Jones, 1992; Sharif, 1989), especially for small, shallow ponds.

Selection Of Method

This manual addresses the free-water evaporation from small shallow ponds. Small shallow ponds can best be modeled with a combination equation when solar radiation and advective energy (drying power of wind) are both used. The Borrelli-Sharif equation (Sharif, 1989; Sharif et al., 1990) is a combination equation with a corrected wind function and improved sensible heat transport model. The equation was tested on measured evaporation for a controlled study in Lubbock, Texas and two separate studies on lake evaporation for Lake Hefner in Oklahoma. The Borrelli-Sharif equation outperformed the lake evaporation equation used by Hill (1994) and the Penman-Monteith equation adapted for lake evaporation (Shuttleworth, 1993). These two equations appear to be the best and latest modified Penman equations used to estimate shallow pond evaporation.

Borrelli-Sharif Equation

The Borrelli-Sharif equation was developed to predict free-water evaporation. As originally recognized by Penman (1948), the physical processes controlling evaporation from a free-water surface are the same as those controlling ET from a crop. The equation as developed by Sharif (1989) is:

$$Evap = \frac{1}{\lambda}\left[\frac{\Delta Q_n}{\Delta\left(1+\frac{1.45C_pT}{\lambda}\right)+\gamma Le_t}\right]$$

$$+\left[\frac{\gamma \Pr_t^{-1}}{\Delta\left(1+\frac{1.45C_pT}{\lambda}\right)+\gamma Le_t}\right]\times\frac{\varepsilon\rho\lambda k_o^2}{P\left[\ln\left(\frac{z-d}{z_o}\right)\right]^2}\times u_z\times(e_z^{*}-e_z) \qquad (19)$$

where

γ = the psychrometric constant (mb/°K)
Δ = slope of the saturated vapor pressure-temperature in the Clausius-Clapeyron equation (mb/°K)
ε = ratio of molecular weight of air to the molecular weight of water vapor ≅ 0.622 (dimensionless)
λ = latent heat of vaporization (cal/gm)
ρ = density of dry air (gm/cm^3)
C_p = specific heat of air at constant pressure (cal/(gm-°K))
d = displacement height of wind profile (m)
e_z = partial water vapor pressure corresponding to the dew point temperature measured at height z (mb)
e_z^{*} = saturated water vapor pressure corresponding to air temperature measured at height z (mb)
Evap = evaporation of water (cm/day)
K_o = von Karman's constant ≅ 0.40 (dimensionless)
Le_t = turbulent Lewis number ≅ Le_t = 1.0 (dimensionless)
Pr_t = turbulent Prandtl number ≅ 0.885 (dimensionless)
Q_n = net solar radiation ($cal/(cm^2$-sec))
T = ambient temperature in degrees absolute (°K)
z = reference height of wind measurement above ground (m)
z_o = aerodynamic roughness (m)

The formula looks like an extension of the well-known combination formula proposed by van Bavel (1966). It should be noted that the proposed formula is free from the requirement of any locally calibrated coefficients, except for predicting the aerodynamic roughness, z_o, which is best locally determined. The formula requires only directly measurable climatological quantities that are routinely reported by first order weather stations.

Limiting Effect of Wind Velocity

All classical models for evaporation of the form proposed by Dalton (Knapp, 1985), Thornthwaite and Holzman (1942), and Penman (1948) consider the rate of evaporation to increase linearly with an increase in wind velocity. This is in contrast with the theoretical considerations of the evaporation problem as reported by Jeffreys (1915), Sutton (1934), and Budyko (1974). They showed the rate of evaporation is proportional to U^n where n varies between 0.50 to 0.76. Observations at Temple, Texas (Richie, 1979) and Bushland, Texas (Steiner et al., 1989) also indicate that the rate of evapotranspiration is not linear with velocity.

The analyses of evaporation data collected over water at Lubbock, Texas (Sharif, 1989) and evapotranspiration data from well-watered cool-season grass at Davis, California (Morgan et al., 1971), showed that water vapor transfer becomes constant as wind velocity increases past some fixed velocity. By experimentation with an evapotranspiration data set (clipped rye grass) from Davis, California, a cutoff velocity of 3 m/s produced the smallest error of prediction for the cool-season grass.

Several findings provide insight into the experimental observation that there is a limiting effect of wind velocity. If water is allowed to evaporate in still air, the rate of evaporation follows Fick's law. If no heat is added or subtracted (no radiation input), then the rate of evaporation increases with increasing wind velocity with corresponding decrease in the temperature of the water surface. An equilibrium between the water surface temperature and the rate of evaporation is reached and becomes constant after a certain "upper limit" of wind velocity is reached. This equilibrium temperature is called the "wet-bulb" temperature or the temperature at which the flow of heat from the air equals that which is released from the water through vaporization. Rich (1961) has shown that for a freely evaporating surface, the evaporation rate becomes "independent of air velocity as the conditions remain turbulent." On the same subject, van Wylen (1962) has reported that, in general, air velocities upwards to 700 feet per minute (3.5 m/s) is the approximate upper limit of the wind velocity over water. Konstaninor (1966) gave an exhaustive account on the effects of wind velocity but reported no conclusive results. However, he pointed out that the magnitude of the wind velocity at which the upper limit is reached may be higher over water than over vegetative surfaces.

Sharif (1989), using evaporation data collected at Lubbock, Texas and data from Lake Hefner in Oklahoma (Crow et al., 1967), found the upper limit of wind velocity to be 3.5 m/s when there was no change in the rate of evaporation as wind velocities increased. Therefore, a cutoff wind velocity of 3.5 m/s was used for any wind velocity greater than 3.5 m/s.

In an operational mode, wind velocities are reported as averages for a period. Gregory (1989) developed frequency distributions of wind velocities given average annual wind velocities. He concluded that the amplitude of yearly wind cycles are proportional to the yearly average wind velocity. Thus, the cumulative probability function can be generated, given the average wind velocity. Furthermore, the coefficient of variation appeared to be constant throughout the year. This allowed the cumulative probability function for both daily and monthly time periods to be generated, given an average wind velocity.

Correction For Average Wind Speed

Gregory (1989) found that the cumulative probability function was essentially the same for all locations tested in the Great Plains. Thus, a single cumulative probability function could represent all areas. The function is:

$$P = 100\left(1 - e^{-A_1\left(1-e^{-A_2 S^{A_3}}\right)S^{A_3}}\right) \tag{20}$$

where

P = cumulative probability, percent
A_1 = 2.034
A_2 = 0.579
A_3 = 1.149
S = velocity ratio of $U/\overline{U}$
U = wind velocity (m/s)
$\overline{U}$ = average wind velocity for the period (m/s).

It was assumed that the above function fits all wind data.

For a given location, the adjusted average wind velocity, U_z, will be less than the average wind velocity when any velocity over 3.5 m/s is reduced to 3.5 m/s. The higher the average wind velocity, the closer the adjusted wind velocity will be to 3.5 m/s, and the lower the wind velocity, the closer the adjusted wind velocity will be to the average wind velocity.

Using Equation 20, the following function for the adjusted wind velocity for a limit of 3.5 m/s is:

$$U_z = 3.5 \times \left(1 - e^{(-0.49\bar{U})}\right) \tag{21}$$

where

U_z = adjusted average daytime wind velocity (m/s)
$\bar{U}$ = average wind velocity (m/s)

The wind corrected for the limit of 3.5 m/s falls within the range of wind velocity correction that would occur for U^n for n between 0.5 and 0.76. This is the theoretical correction as proposed by Jeffreys (1915), Sutton (1934), and Budyko (1974).

Selection of Aerodynamic Roughness (z_o)

The aerodynamic roughness, z_o, is a constant of integration in the "log-law" profile that describes the variation of wind velocity with height. It represents the height where the log profile of wind velocity, when extrapolated to the surface, vanishes. The actual numerical value of z_o can only be determined by experimentation.

Numerous researchers have attempted to determine z_o over free water surfaces with mixed results. Marciano and Harbeck (1954) found z_o values between 0.5 and 1.2 cm with z_o increasing with increased wind velocities. They reported a z_o of 0.94 cm for a wind speed of 7.56 m/s at a height of 2 m. At the same lake, Lake Hefner, Lettau and Zabransky (1968) reported a z_o of 0.235 cm. They argued that the 0.235 cm value was more reasonable than the values reported by Marciano and Harbeck (1954).

Selection Of z_o

Shuttleworth (1993) reported that the proper z_o to use in the Penman-Monteith equation when used for free water evaporation was 0.137 cm. Furthermore, Shuttleworth (1993) states it is the same value implicitly assumed by Penman (1948) in his original work on free water evaporation. The Borrelli-Sharif equation was used to minimize the percent error by calibrating z_o using data from Lake Hefner in Oklahoma and Lubbock, Texas. The optimum z_o was 0.15 cm, very close to the 0.137 cm recommended by Shuttleworth (1993). For the prediction of free-water evaporation, a value of 0.15 was selected as the best value for z_o.

Contours of Free-Water Evaporation for Shallow Ponds

Presented in Figures 37 - 48 are contours of mean monthly free-water evaporation for shallow ponds. Several climatic stations in New Mexico, Oklahoma, Arkansas, and Louisiana were used to help define the contours across the State of Texas. In Table 26, Evaporation rates are given for specific locations in Texas.

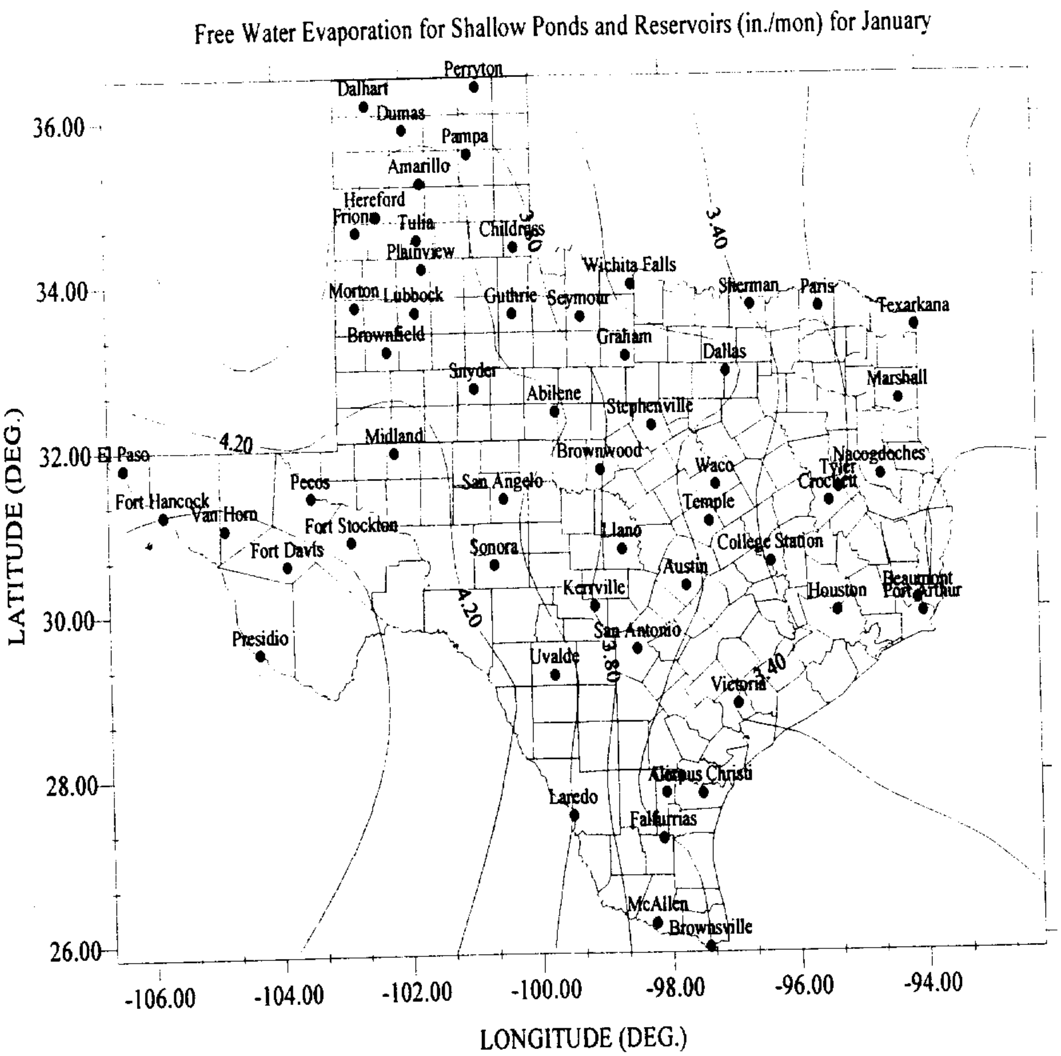


Figure 37.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for January.

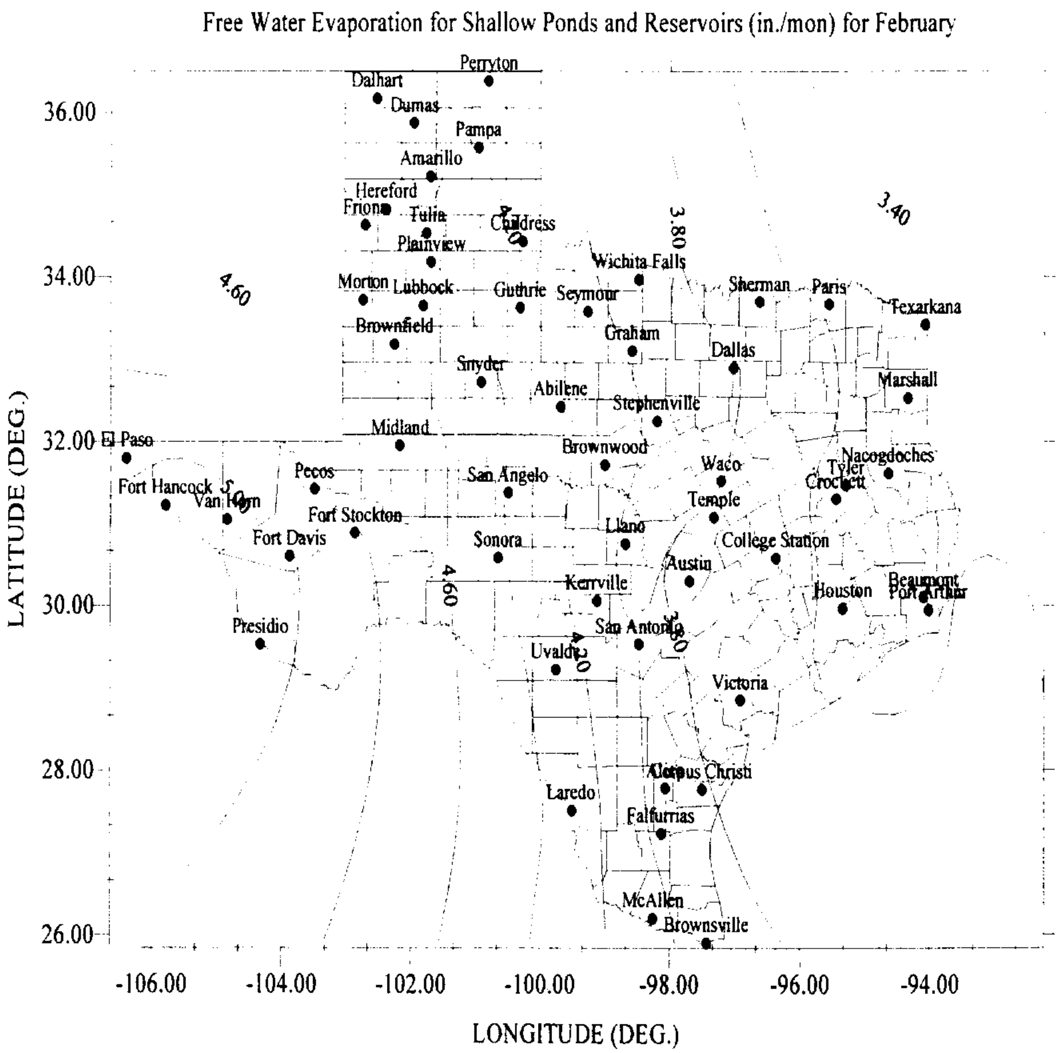


Figure 38.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for February.

Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for March

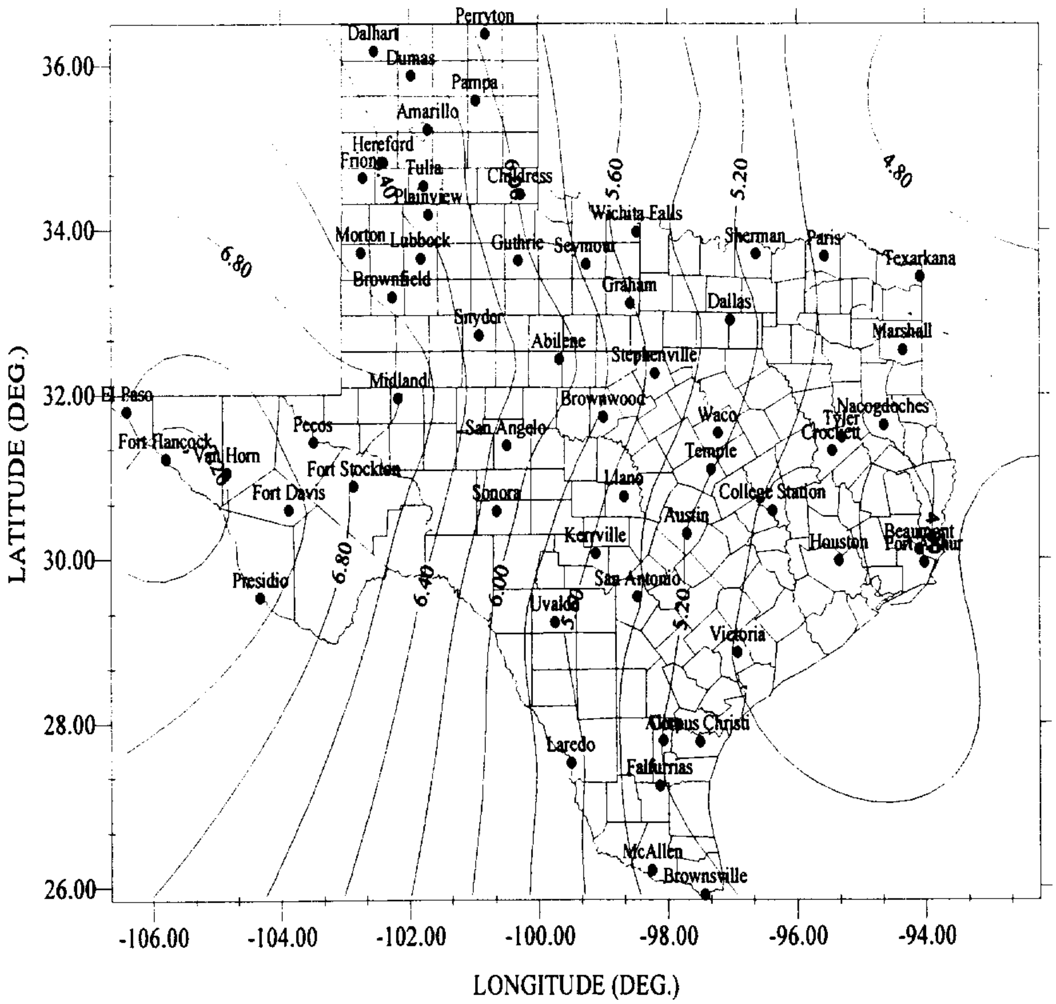


Figure 39.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for March.

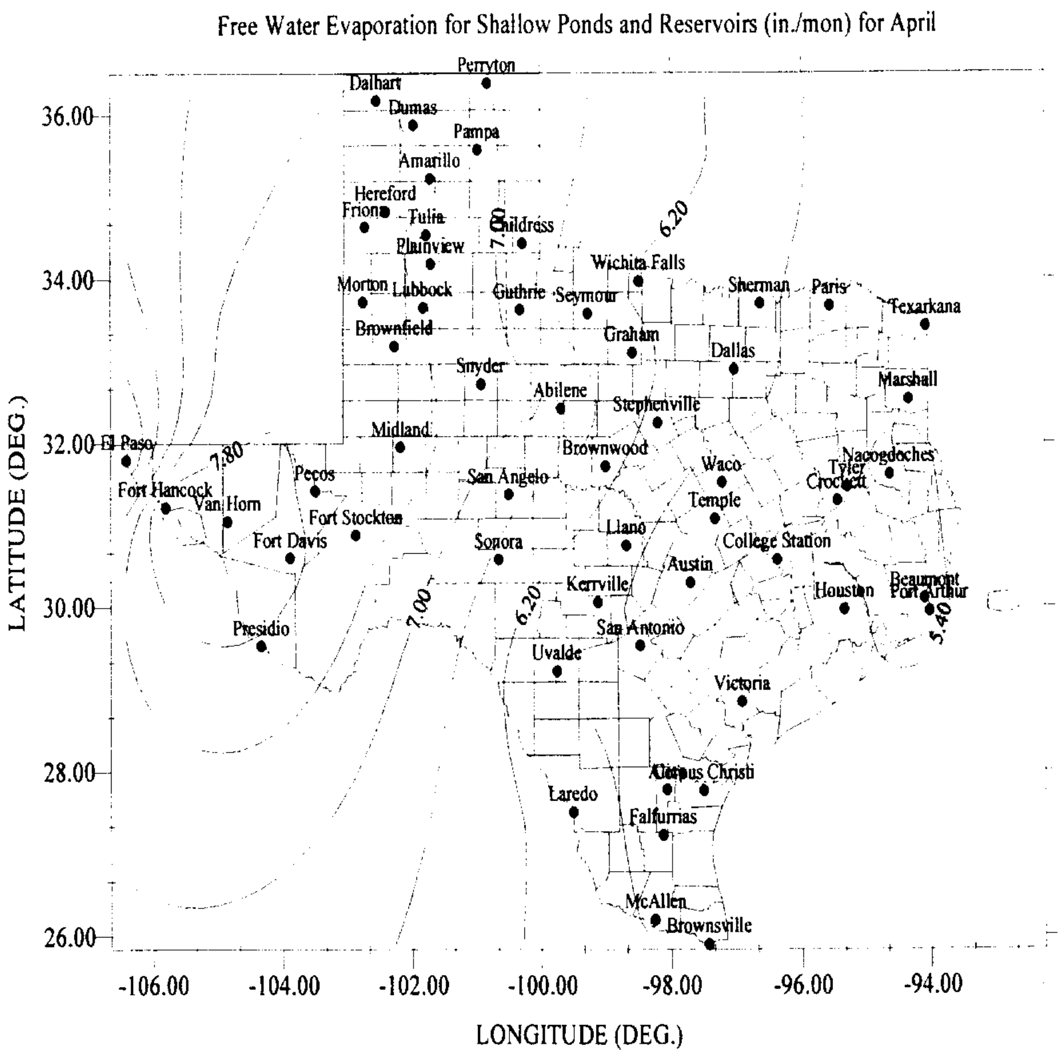


Figure 40.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for April.

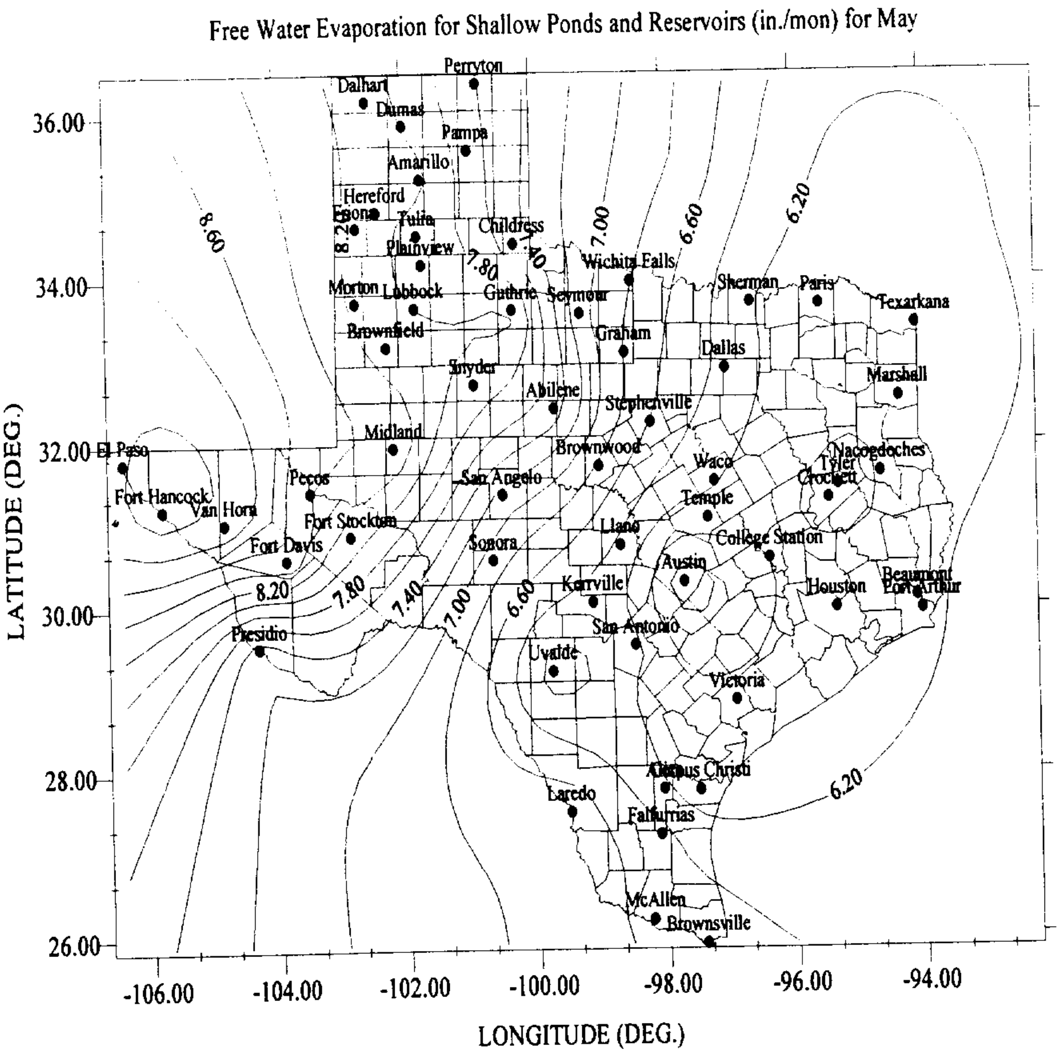


Figure 41.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for May.

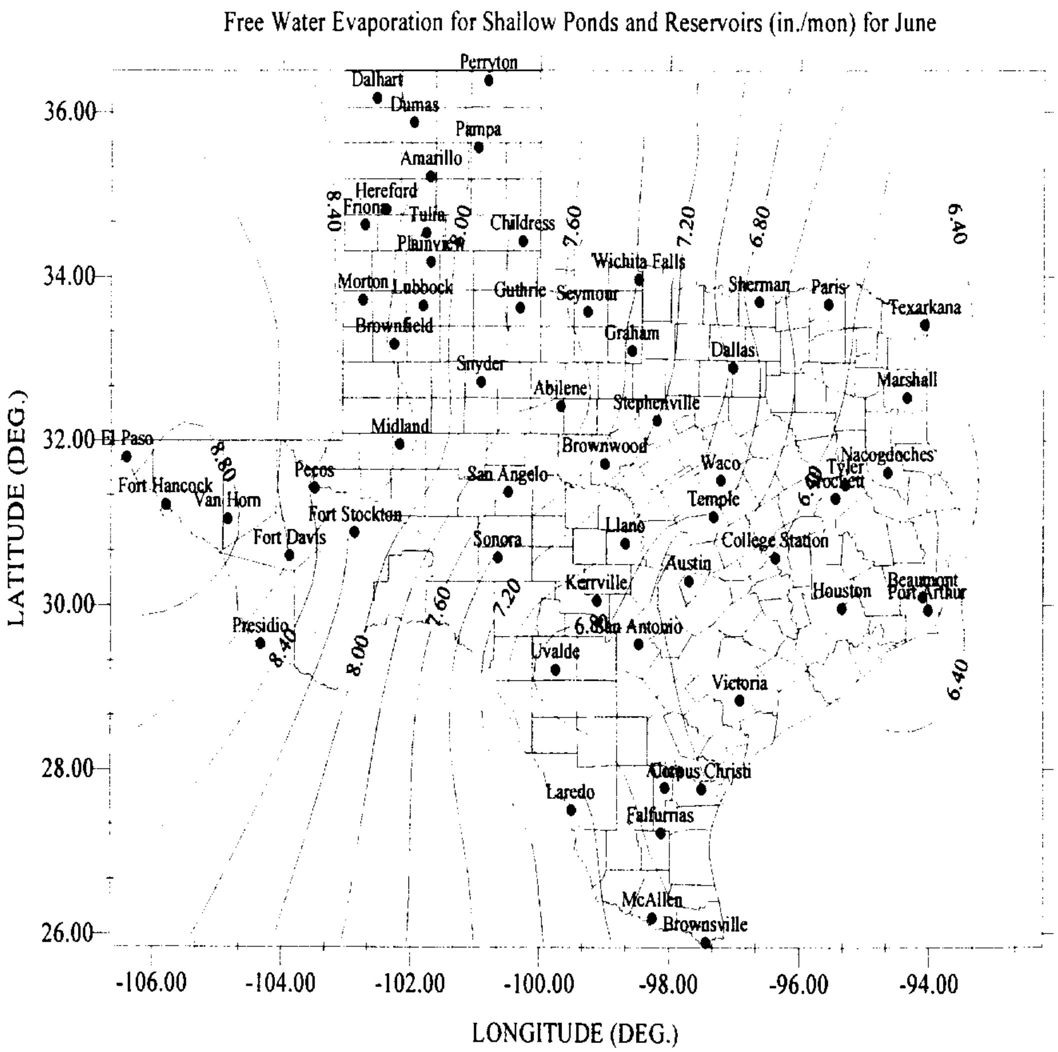


Figure 42.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for June.

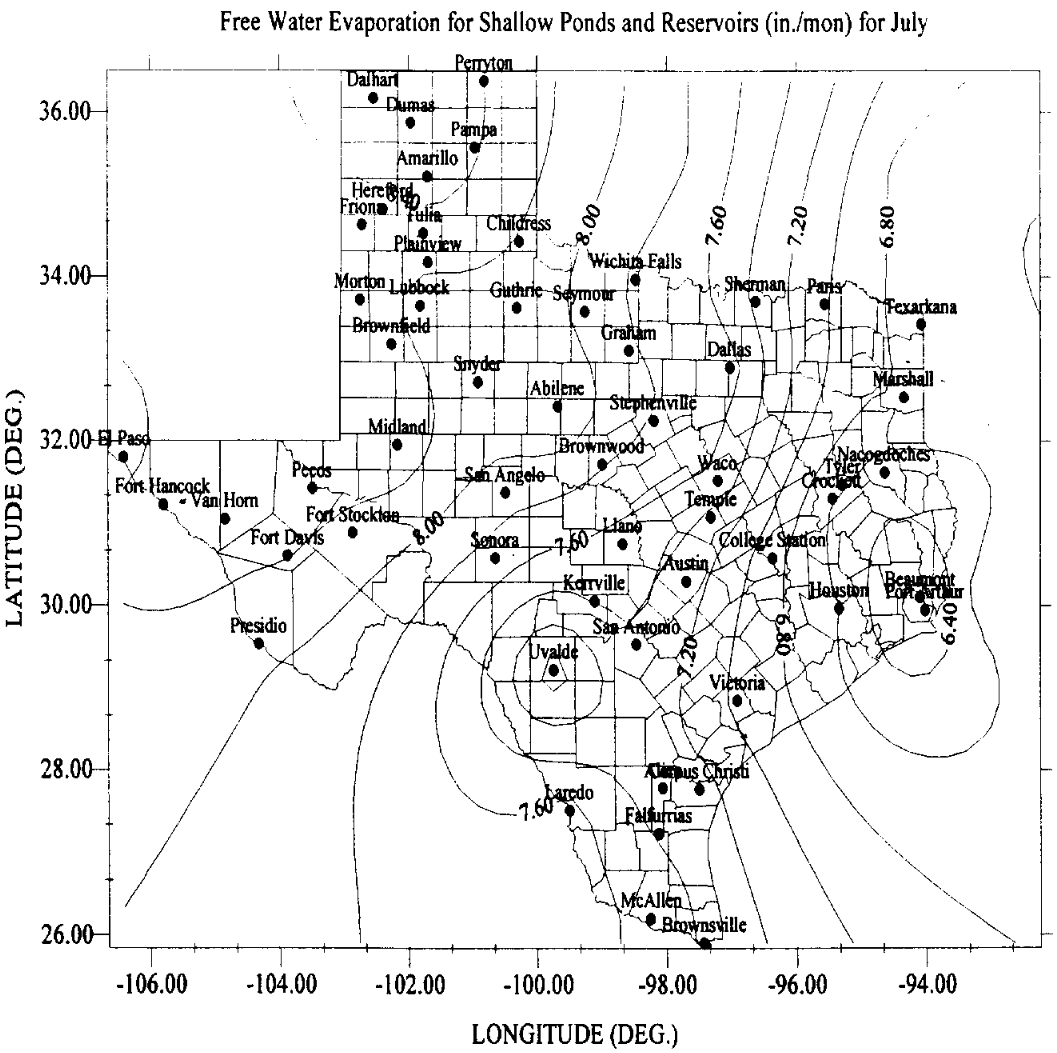


Figure 43.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for July.

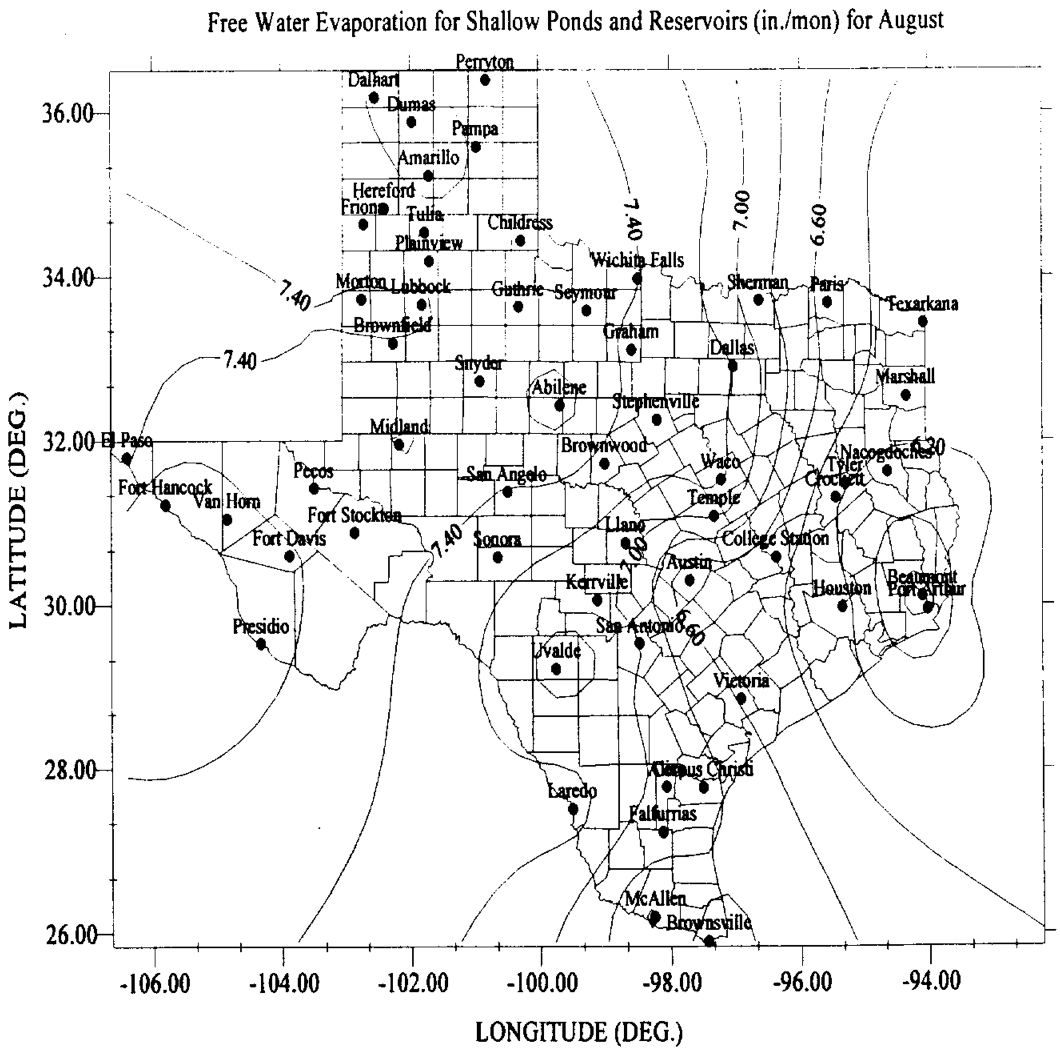


Figure 44.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for August.

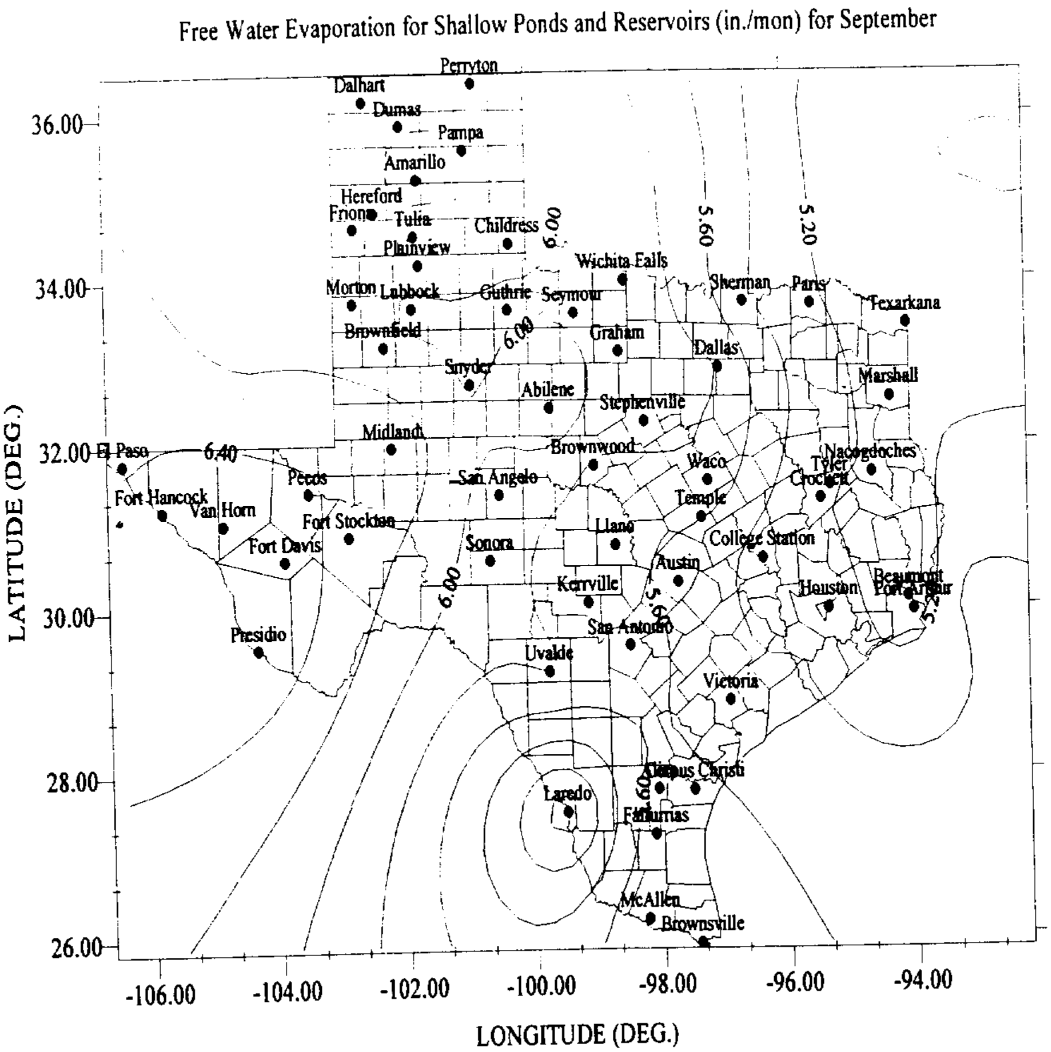


Figure 45.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for September.

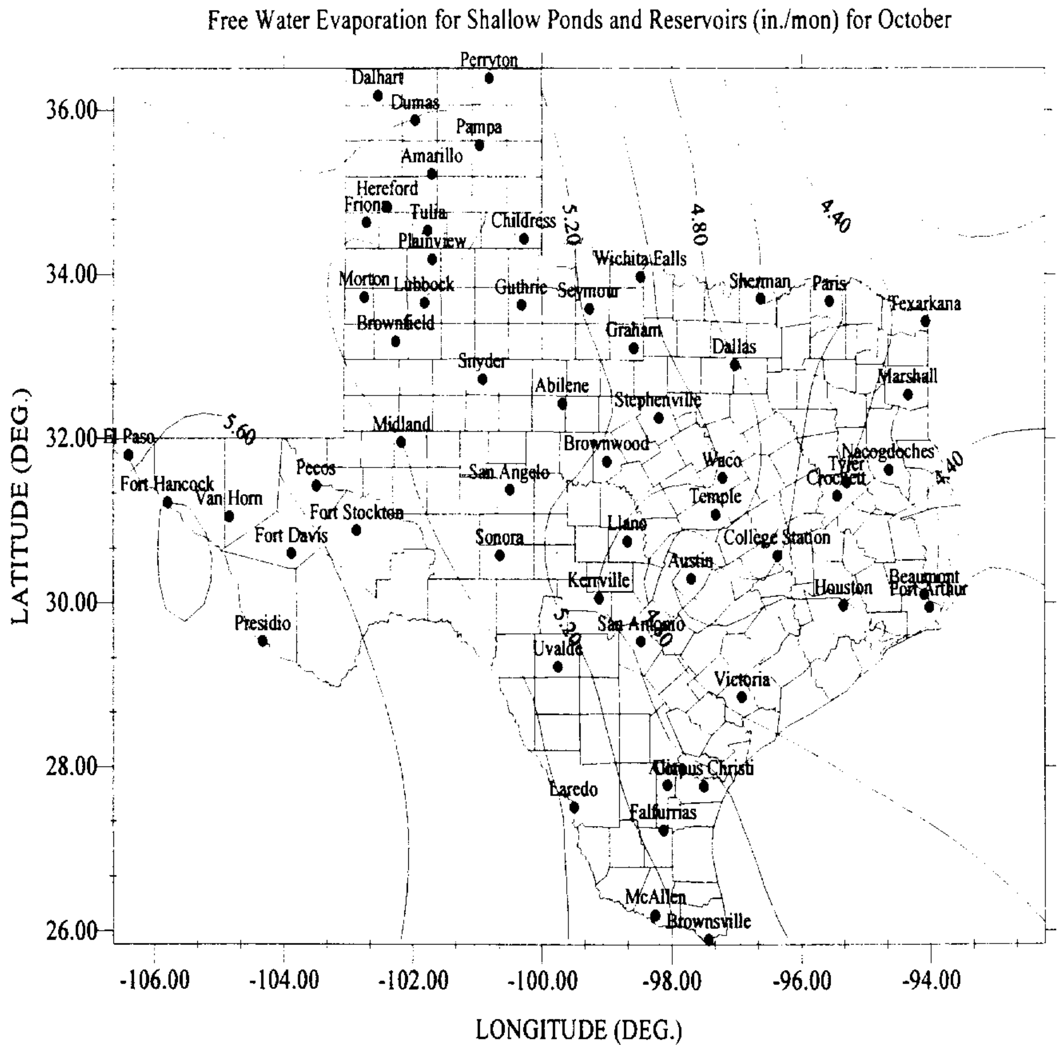


Figure 46.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for October.

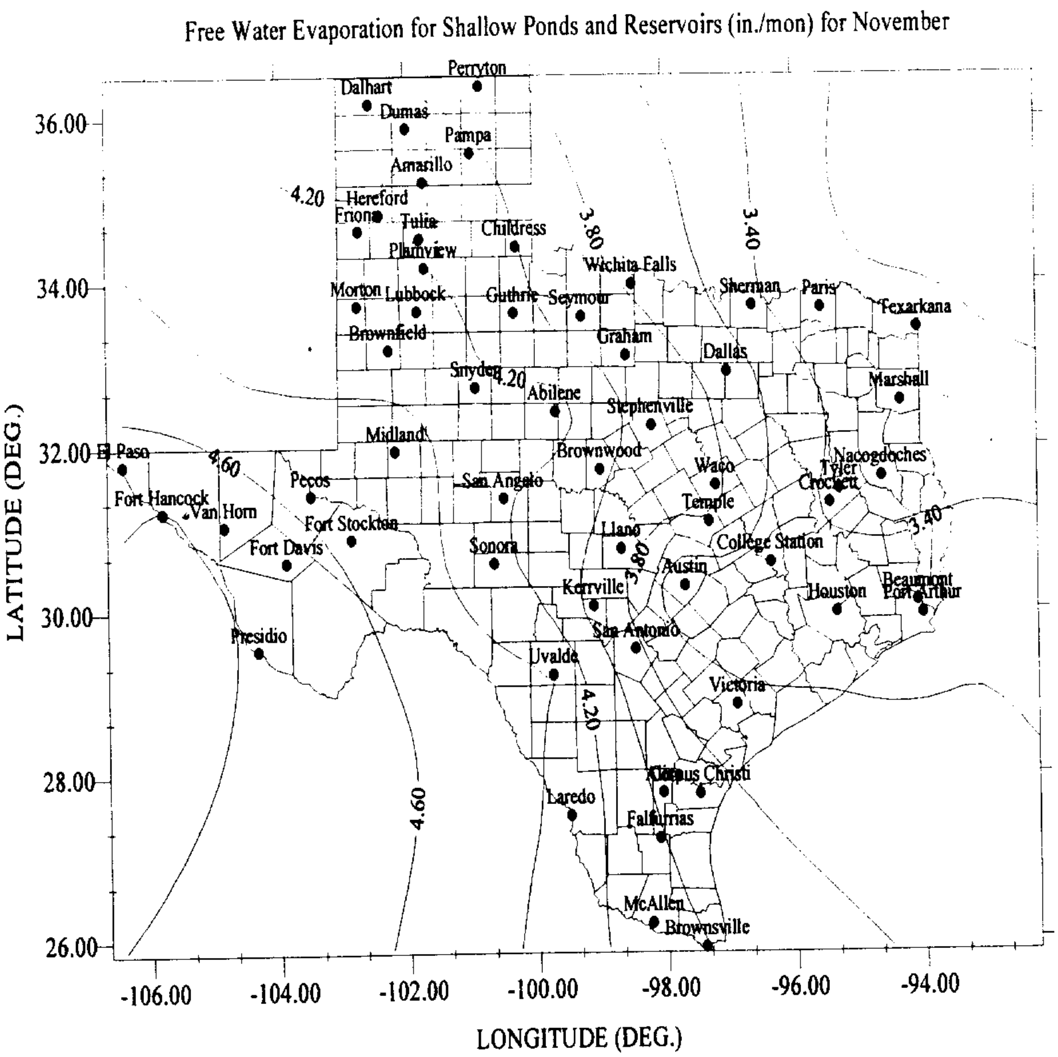


Figure 47.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for November.

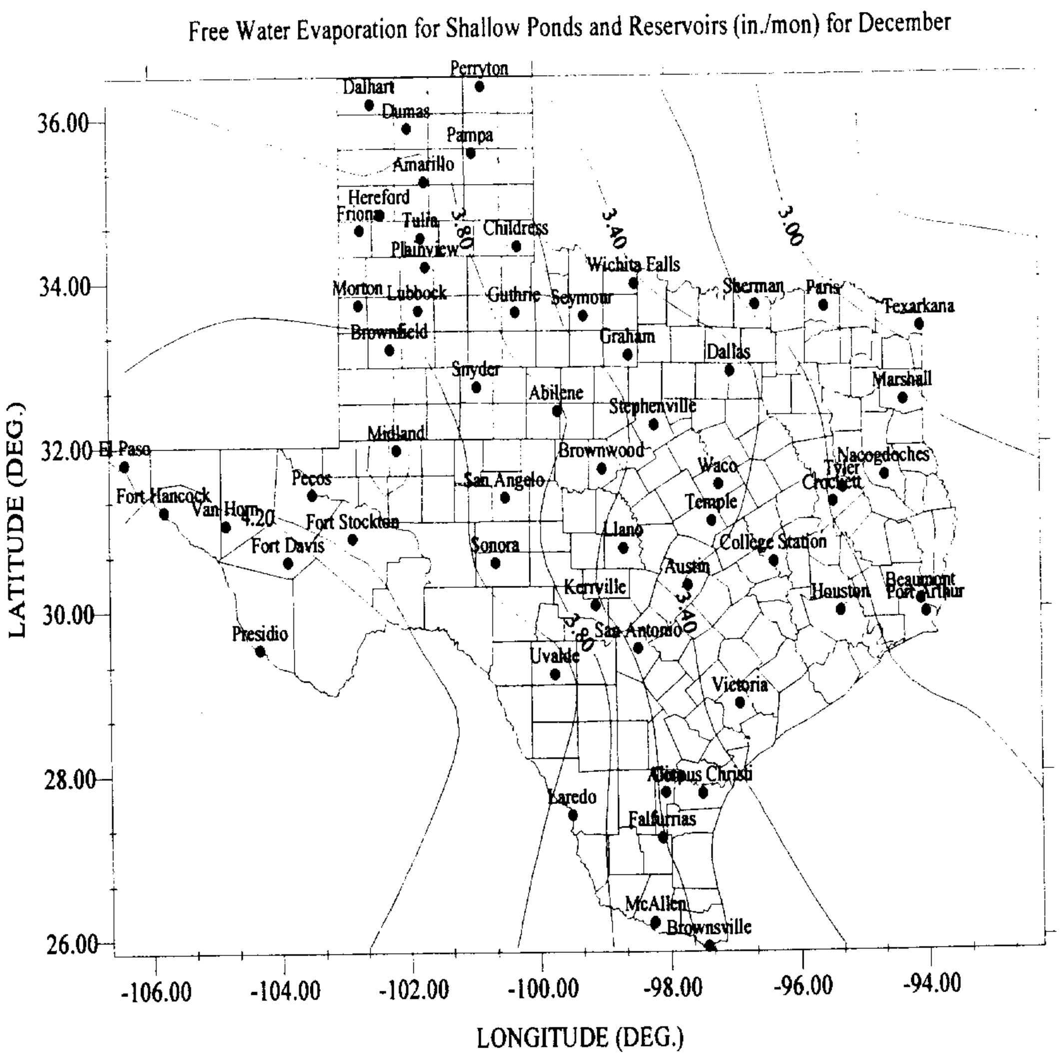


Figure 48.-Free Water Evaporation for Shallow Ponds and Reservoirs (in./mon) for December.

Table 26.-Free Water Evaporation for Shallow Ponds and Reservoirs (inches per month).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Abilene	4.08	4.24	6.14	7.04	7.54	7.83	8.23	7.70	6.19	5.39	4.30	3.85	72.51
Alice	3.40	3.91	5.18	5.61	6.22	6.69	7.29	6.96	5.69	5.04	3.96	3.57	63.52
Amarillo	4.24	4.48	6.44	7.50	8.06	8.20	8.52	7.68	6.30	5.58	4.30	3.94	75.24
Austin	3.67	3.67	5.19	5.45	5.63	6.30	7.29	6.38	5.51	4.43	3.43	3.39	60.35
Beaumont	3.14	3.53	4.61	5.11	6.01	6.18	6.11	5.65	4.91	4.48	3.43	3.07	56.24
Brownfield	4.06	4.51	6.55	7.45	8.10	8.17	8.24	7.40	6.06	5.33	4.29	4.03	74.18
Brownsville	3.60	3.90	5.25	5.79	6.54	6.82	7.37	6.89	5.71	5.09	4.01	3.56	64.54
Brownwood	3.80	4.11	5.77	6.31	6.77	7.32	7.81	7.34	5.76	5.15	4.03	3.67	67.84
Childress	3.88	4.19	5.99	6.85	7.45	7.74	8.19	7.46	6.04	5.32	4.01	3.69	70.81
College Station	3.38	3.69	4.95	5.33	6.01	6.38	6.86	6.46	5.31	4.60	3.52	3.34	59.83
Corpus Christi	3.56	3.82	5.12	5.57	6.09	6.61	7.28	6.87	5.65	5.06	3.90	3.52	63.07
Crockett	3.20	3.53	4.88	5.41	5.95	6.25	6.59	6.21	5.21	4.40	3.36	3.18	58.16
Dalhart	3.89	4.29	6.33	7.46	8.11	8.29	8.45	7.61	6.15	5.35	4.07	3.69	73.69
Dumas	3.91	4.26	6.22	7.35	7.99	8.16	8.51	7.63	6.18	5.39	4.06	3.69	73.35
El Paso	4.30	4.91	6.99	5.57	8.98	8.69	8.12	7.35	6.37	5.53	4.67	4.04	75.53
Falfurrias	3.63	3.95	5.21	5.65	6.48	6.74	7.38	6.88	5.73	5.13	4.01	3.60	64.39
Fort Davis	4.51	5.02	7.09	7.90	8.59	8.62	8.21	7.64	6.53	5.71	4.73	4.32	78.87
Fort Hancock	4.40	5.19	7.35	8.35	9.14	9.03	8.37	7.81	6.56	5.82	4.82	4.29	81.14
Fort Stockton	4.37	4.81	6.78	7.53	8.11	8.16	8.13	7.44	6.30	5.50	4.55	4.18	75.87
Fort Worth	3.69	3.83	5.34	6.06	6.36	7.00	7.69	7.22	5.82	4.82	3.74	3.55	65.12
Friona	4.04	4.40	6.47	7.52	8.16	8.31	8.34	7.50	6.15	5.41	4.23	3.87	74.40
Graham	3.67	3.98	5.61	6.30	6.79	7.37	7.81	7.35	5.91	5.07	3.92	3.54	67.31
Guthrie	3.96	4.22	6.05	6.87	8.07	7.74	8.11	7.44	5.97	5.28	4.08	3.74	71.54
Hereford	4.00	4.38	6.37	7.47	8.06	8.25	8.35	7.49	6.12	5.42	4.20	3.81	73.94

Table 26.-Free Water Evaporation for Shallow Ponds and Reservoirs (inches per month) (continued).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Houston	3.40	3.58	4.89	5.52	6.14	6.39	6.61	6.29	5.42	4.62	3.55	3.29	59.70
Kerrville	3.78	4.09	5.58	5.87	6.32	6.87	7.42	7.04	5.62	4.98	3.92	3.60	65.07
Laredo	4.01	4.33	5.68	6.05	6.74	7.11	7.67	7.31	4.85	5.38	4.33	3.92	67.4
Llano	3.76	3.96	5.51	5.91	6.37	6.98	7.52	7.08	5.66	4.96	3.90	3.52	65.1
Lubbock	4.22	4.52	6.51	7.44	8.00	8.10	8.16	7.36	5.96	5.40	4.32	3.97	74.0
Marshall	3.13	3.52	4.86	5.42	6.03	6.30	6.79	6.31	5.14	4.31	3.31	3.02	58.1
McAllen	3.72	4.06	5.33	5.75	6.53	6.85	7.55	6.54	5.82	5.25	4.08	3.70	65.2
Midland	4.40	4.75	6.85	7.69	8.38	8.31	8.34	7.64	6.40	5.41	4.53	4.26	77.0
Morton	4.03	4.49	6.53	7.48	8.15	8.30	8.26	7.38	6.07	5.36	4.26	3.96	74.3
Nacogdoches	3.18	3.60	4.81	5.32	6.00	6.28	6.50	6.13	5.19	4.36	3.37	3.12	57.9
Pampa	3.91	4.17	6.07	7.11	7.70	7.95	8.42	7.59	6.17	5.40	4.04	3.65	72.2
Paris	3.19	3.59	4.98	5.65	6.07	6.46	7.01	6.54	5.23	4.68	3.28	3.04	59.7
Pecos	4.26	4.76	6.87	7.70	8.40	8.36	8.28	7.41	6.42	5.51	4.53	4.11	76.6
Perryton	3.70	4.10	5.97	7.02	7.61	7.91	8.40	7.53	6.11	5.32	3.87	3.48	71.0
Plainview	4.03	4.39	6.31	7.29	7.89	8.09	8.22	7.50	6.08	5.43	4.18	3.88	73.3
Port Arthur	3.23	3.57	4.72	5.22	6.07	6.21	6.11	5.75	5.05	4.57	3.50	3.11	57.1
Presidio	4.57	5.07	7.05	7.76	7.24	8.50	8.04	7.66	6.57	5.75	4.78	4.37	77.3
San Angelo	4.03	4.38	6.10	6.69	7.12	7.58	7.86	7.38	5.89	5.25	4.21	3.88	70.4
San Antonio	3.72	4.01	5.44	5.81	6.27	6.79	7.41	7.05	5.76	4.97	3.84	3.57	64.6
Seymour	3.67	4.06	5.76	6.29	7.06	7.51	7.94	7.46	5.97	5.18	3.86	3.50	68.3
Sherman	3.37	3.64	5.12	5.86	6.21	6.69	7.35	6.86	5.42	4.58	3.43	3.14	61.7
Snyder	3.99	4.47	6.30	7.14	7.91	7.86	8.10	7.51	5.98	5.20	4.22	3.88	72.5
Sonora	4.07	4.43	6.11	6.53	6.90	7.37	7.73	7.28	5.90	5.31	4.24	3.92	69.8

Table 26.-Free Water Evaporation for Shallow Ponds and Reservoirs (inches per month) (continued).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Stephenville	3.65	3.96	5.57	6.10	6.60	7.19	7.79	7.27	5.86	5.12	3.93	3.55	66.6
Temple	3.53	3.77	5.21	5.56	6.13	6.78	7.35	7.04	5.60	4.92	3.80	3.44	63.1
Texarkana	3.11	3.52	4.89	5.48	6.08	6.35	6.70	6.28	5.13	4.33	3.31	2.99	58.2
Tulia	4.04	4.35	6.28	7.29	7.91	8.08	8.29	7.50	6.09	5.42	4.19	3.82	73.3
Tyler	3.20	3.55	4.87	5.43	5.97	6.30	6.64	6.21	5.22	4.38	3.36	3.17	58.3
Uvalde	4.15	4.31	5.62	5.76	6.09	6.61	6.87	6.90	5.84	5.34	4.41	4.16	66.0
Van Horn	4.46	5.06	7.19	8.11	8.93	8.85	8.30	7.67	6.56	5.76	4.74	4.21	79.8
Victoria	3.38	3.65	4.98	5.47	6.06	6.49	6.95	6.58	5.43	4.75	3.64	3.29	60.7
Waco	3.47	3.81	5.26	5.63	6.22	6.93	7.56	7.26	5.76	5.02	3.84	3.45	64.2
Wichita Falls	3.56	3.87	5.47	6.16	6.81	7.41	7.77	7.42	5.94	5.05	3.79	3.41	66.6

Borrelli - Sharif Model for Free-Water Evaporation

The Borrelli-Sharif model is an extension of the well-known van Baval (1966) formula for estimating evapotranspiration. It should be noted that the Borrelli-Sharif formula is free from any locally calibrated coefficients. The one factor that requires some judgment is the selection of z_0. From the literature and by calibration with measured evaporation from a controlled pond, it appeozrs the best value for z_0 is 0.15 cm. The Borrelli-Sharif model has a corrected wind function and an improved sensible heat transport model.

Input the Variables

Lat := 33.65	Latitude in degrees
DOY := 1	Julian Day
Elev := 991	Meters
Tmax := 18.3	Maximum Temperature, Degrees Centigrade
Tmin := 10	Minimum Temperature, Degrees Centigrade
Zo := 0.15	Aerodynamic roughness, cm
Rh := 65	Relative humidty, percent
U := 678	Wind run, kilometers per day at 2 meters
nN := 65	Percent possible sunshine

***********************Start of Calculations*************************

$Ta := \frac{Tmax + Tmin}{2}$ Mean Temperature, Degrees Centigrade $Ta = 14.15$

$\rho := 0.00123 - 0.000034 \cdot \frac{Elev}{1000}$ ρ is the atmospheric density in g/cm³ $\rho = 1.196 \cdot 10^{-3}$

$BP := 1013 - 0.1055 \cdot Elev$ $BP = 908.449$

$\Delta := \frac{25029.9221}{(Ta + 237.3)^2} \cdot \exp\left(\frac{Ta \cdot 17.2694}{Ta + 237.3}\right)$ Δ is the slope of the saturation pressure-temperature curve, mb/C $\Delta = 1.046$

$\lambda := 595.9 - 0.55 \cdot Ta$ λ is the latent heat, cal/cm[3] $\lambda = 588.117$

$\gamma := \dfrac{0.24 \cdot BP}{0.622 \cdot \lambda}$ γ is the psychrometric constant, mb/C $\gamma = 0.596$

$uz := \dfrac{U \cdot 1000}{24 \cdot 60 \cdot 60}$ $uz = 7.847$

$uza := 3.5 \cdot \left(1 - e^{-0.49 \cdot uz}\right)$ $uza = 3.425$ Adjusted wind speed such that the average wind speed does not exceed 3.5 m/s.

$A := 753.6 - 6.53 \cdot Lat + Elev \cdot 0.0057 \cdot 3.28$

$B := -7.1 + 6.40 \cdot Lat + Elev \cdot 0.0030 \cdot 3.28$

$Rso := A + B \cdot \cos\left[(0.9863 \cdot (DOY - 170)) \cdot \dfrac{\pi}{180}\right]$ Clear day solar radiation at surface, lang $Rso = 340.243$

$Ra := \dfrac{Rso}{0.75}$ Solar radiation at top of atmosphere, lang $Ra = 453.657$

$eoz := 6.1078 \cdot \exp\left(\dfrac{17.269388 \cdot Ta}{Ta + 237.3}\right)$ Saturated vapor pressure at mean air temp, mb $eoz = 16.141$

$ed := eoz \cdot \dfrac{Rh}{100}$ $ed = 10.492$ Actual vapor pressure, mb

$Lewis\_no := 1$ Value of Lewis Number

$Pr\_no := \dfrac{1}{1.13}$ Value of the inverse turbulent Prandtl number

$k := 0.40$ von Karman constant

$a1 := 0.26 + 0.1 \cdot \exp\left[-(0.0154 \cdot (DOY - 176))^2\right]$ $a1 = 0.26$

$\varepsilon := a1 - 0.044 \cdot ed^{0.5}$

$Ts4 := 0.5 \cdot \left[(Tmax + 255.4)^4 + (Tmin + 255.4)^4\right]$

$\sigma := 11.71 \cdot 10^{-8}$ Stephan-Boltzman Constant

$Rbo := \varepsilon \cdot \sigma \cdot Ts4$ Net outgoing longwave radiation on a cleozr day, lang $Rbo = 72.77$

$Rs := \left(0.35 + 0.65\cdot\frac{nN}{100}\right)\cdot Rso$ $Rs = 262.837$

$jb1 := \frac{Rs}{Rso}$

$a := if(jb1 > 0.7, 1.126, 1.017)$ $a = 1.126$

$b := if(jb1 > 0.7, -0.07, -0.06)$ $b = -0.07$

$Rb := \left(a\cdot\frac{Rs}{Rso} + b\right)\cdot Rbo$ $Rb = 58.204$

$\alpha := 0.06$ Albeto for water

$Rn := (1 - \alpha)\cdot Rs - Rb$ Net radiation, lang $Rn = 188.863$

$cp := 0.24$ Specific heat of air at constant pressure, cal-gm^{-1}-K^{-1}

$$Part1 := \frac{\Delta\cdot Rn}{\Delta\cdot\left[1 + \frac{1.45\cdot cp\cdot(Ta + 273)}{\lambda} + \gamma\cdot Lewis\_no\right]}$$ $Part1 = 106.948$

$$Part2 := \frac{\gamma\cdot Pr\_no^{-1}}{\Delta\cdot\left[1 + \frac{1.45\cdot cp\cdot(Ta + 273)}{\lambda} + \gamma\cdot Lewis\_no\right]}$$ $Part2 = 0.365$

$$Part3 := \frac{0.622\cdot\rho\cdot\lambda\cdot k^2\cdot uza\cdot(eoz - ed)\cdot 6000\cdot 60\cdot 24}{BP\cdot\ln\left(\frac{200}{Zo}\right)^2}$$ $Part3 = 248.886$

$E := \frac{Part1 + Part2\cdot Part3}{\lambda}\cdot 10$ $E = 3.36122$ Evaporation, mm.day

$E := \frac{E}{25.4}$ $E = 0.132$ Evaporation, inches/day

The complete Borrelli-Sharif equation--inches per day

$$E := \frac{\left[\frac{\Delta \cdot Rn}{\Delta \cdot \left[1 + \frac{1.45 \cdot cp \cdot (Ta + 273)}{\lambda}\right] + \gamma \cdot Lewis\_no} + \frac{\gamma \cdot Pr\_no^{-1}}{\Delta \cdot \left[1 + \frac{1.45 \cdot cp \cdot (Ta + 273)}{\lambda}\right] + \gamma \cdot Lewis\_no} \cdot \frac{0.622 \cdot \rho \cdot \lambda \cdot k^2 \cdot uza \cdot (eoz - ed) \cdot 6000 \cdot 60 \cdot 24}{BP \cdot \ln\left(\frac{200}{Zo}\right)^2}\right] \cdot 10}{\lambda \cdot 25.4}$$

$$E = 0.132 \ \frac{inches}{day}$$

Chapter 6

Application of Evapotranspiration Data

General Design Procedure for Center Pivot Hydraulic Capacity

One of the more common applications of mean annual consumptive use is in the design of irrigation systems. Part of every design is the determination of the maximum hydraulic capacity of the system. This must be determined even though in most situations, the actual ET of the crop is not known. The designer must depend on estimates of ET_{crop} for the particular location in question.

This manual provides a relatively simple method to estimate ET_{crop} for the major crops grown in Texas. For purposes of determining the hydraulic design capacity of an irrigation system, the mean consumptive use values can be used with some reliability. Shown below is a recommended procedure for the hydraulic sizing of a center pivot spray irrigation system.

In ASAE Monograph No. 3 (Jensen, 1983a), a general equation was presented for determining the quantity of water needed by a center pivot or the hydraulic design capacity of a center pivot system. The general equation is as follows:

$$Q = K\frac{ET_{peak} \times A \times t_{bi}}{EA \times t_l} \qquad (22)$$

where

Q = water needed by the center pivot or hydraulic design capacity (gpm)
A = the area irrigated by the lateral (acres)
EA = water application efficiency (decimal)
ET_{peak} = the peak use rate of the crop (in./day)
K = 18.9 (a constant depending on the units used)
t_{bi} = the time between irrigation events (days)
t_l = the lateral operating time for one irrigation (days)

In extreme cases, the time between irrigation events, t_{bi}, and the lateral operating time for one irrigation may be the same. In other words, the center pivot system is just capable of providing adequate water for the crop. Normally 10 percent downtime is common for most center pivot systems. For purposes of this discussion, which will not explore all alternative methods of sizing center pivot systems, a 10 percent down time will be assumed. This will result in t_l being 90 percent of the value of t_{bi}.

The EA for spray type center pivots are generally taken to be 90 percent for design purposes. The actual value for EA will depend on both management and the designer of the spray head package for the system.

ET_{peak} Determined Using Empirical Formula

This manual can provide an estimate for the peak rate of evapotranspiration, ET_{peak}. As one might envision, there is more than one way to estimate ET_{peak}. A long established method is one that has its origins in the Soil Conservation Service and is described in Jensen (1983a). This empirical method predicts ET_{peak} as a function of mean monthly values of ET_{crop}. The equation is:

$$ET_{peak} = 0.034 \times ET_{crop}^{1.09} \times d_n^{-0.09} \qquad (23)$$

where

ET_{peak} = estimated peak daily ET_{crop} (in./day)
d_n = net depth of irrigation water applied during a normal irrigation (in.)
ET_{crop} = the highest mean monthly ET_{crop} during the crop growing season (in./mon)

Example:

Using "**Example 2**" in Chapter 3 (the crop was corn grain at Pecos, TX) the highest mean monthly ET_{crop} is July with 10.59 inches. For this particular application, d_n would be the depth of water needed to bring the soil moisture up to a desired soil moisture level. During the month with the highest ET_{crop}, leaching is normally not practiced (Keller and Bliesner, 1990). For the purposes of this example, d_n is set at 1.25 inches. Equation 23 provides the following estimate of ET_{peak}:

$$ET_{peak} = 0.034 \times 10.59^{1.09} \times 1.25^{-0.09} = 0.436\,(\text{in./day}) \qquad (24)$$

This procedure estimates ET_{peak} (0.436 inches/day) to be approximately 27 percent higher than ET_{crop} (0.342 inches/day). If we look at the variation of ET_o shown in Figure 24 for El Paso, one would have to conclude this would be a very safe design with a very small probability that ET_{peak} would be exceeded in any year ($ET_o \times K_c \cong 13$ in./mon or 0.42 in./day for a 1 in a 100 year probability of occurrence).

ET_{peak} Using FAO-24 Method

Doorenbos and Pruitt (1977) provided a set of curves that would estimate ET_{peak} that would meet ET_{crop} 3 out of 4 years or a 75 percent chance ET_{peak} would not be exceeded. One good feature is there are curves for different types of climate—a feature of great value in a climate-diverse state such as Texas. As above, the ET_{crop} for the month with the highest ET_{crop} is needed (see Figure 49). In addition, the irrigation depth per application or the depth of readily available soil moisture is needed. Although the irrigation depth per application was not defined by Doorenbos and Pruitt (1977), it appears to be the same as the d_n used above. Using the same set of conditions as above and using Figure 49, ET_{peak} would be 1.14 times the ET_{crop} (inches/day) or 0.390 inches/day. This appears to be a reasonable value after reviewing the ET_o variation at El Paso (Figure 24).

Other Considerations

This manual can be used to provide basic information needed to design center pivot irrigation systems—ET_{peak}. There are, of course, several methods for determining ET_{peak} with the two most cited methods presented above. There are other considerations required to make a proper design decision about hydraulic capacity. A major consideration is that the crop used for ET_{crop} should be the crop with the highest potential ET_{crop} that may be irrigated by the system. The crop(s) may change from year to year, but the irrigation system will be equipment that will be in place for 15 to 20 years. This manual can aid in the determination of the crop with the greatest ET_{peak}.

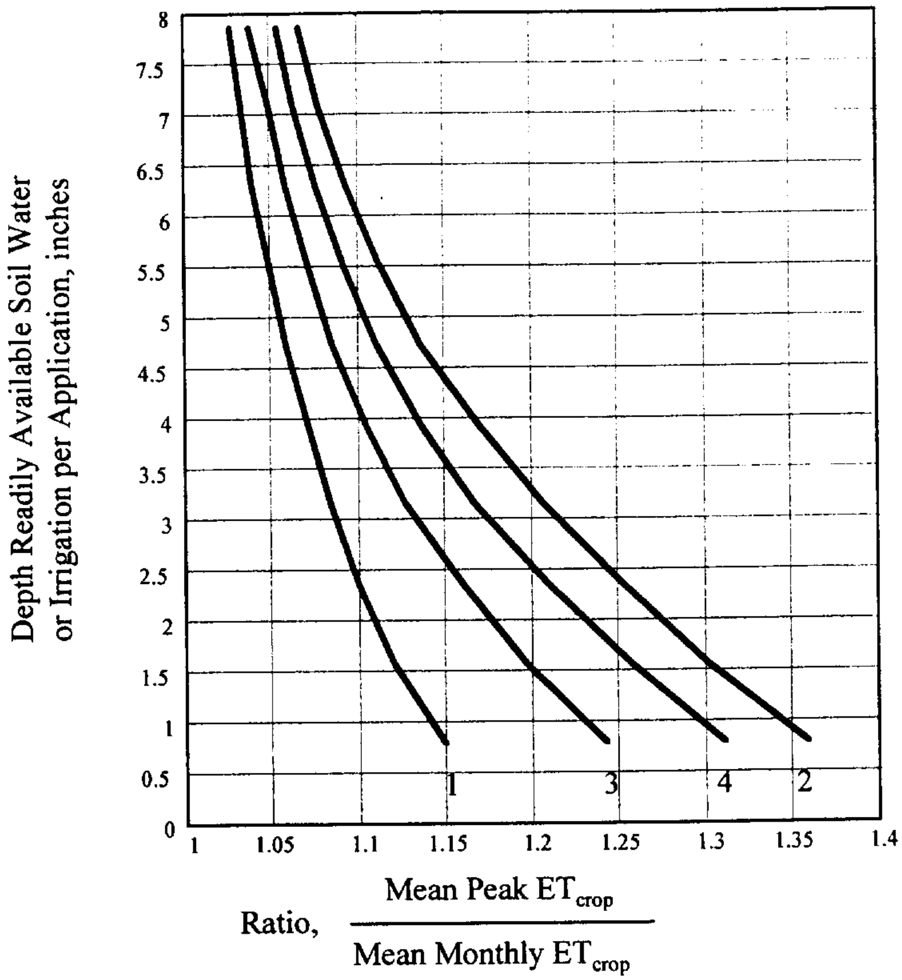


Figure 49. Ratio of 75 Percent Probability ET_{peak} to ET_{crop} for Maximum Month Computed Using Mean Climatic Data as a Function of Climate (Adapted from Doorenbos and Pruitt, 1977).

1. Arid and semi-arid climates and those with predominantly clear weather conditions during month of peak ET_{crop}.
2. Mid-continental climates and sub-humid to humid climates with highly variable cloudiness in month of peak ET_{crop}.
3. Mid-continental climates with variable cloudiness and mean ET_0 of 0.2 inches per day.
4. Mid-continental climates with variable cloudiness and mean ET_0 of 0.4 inches per day.

Water Transfer

In 1992, there were 1220 active water rights along the Texas portion of the Rio Grande (Jonish et al., 1996). Jensen (1997) reported 44 entities in 1996 acquired water rights—transferred water from one entity to another. Most of the transfers, however, were for one year. Nevertheless, the transfer of water from one user to another potentially affects all downstream water right holders along the Rio Grande.

The primary participants in a water transfer are the buyer and seller. However, in the Western states, the primary participants must demonstrate there are no injuries to third parties (National Research Council, 1992). Kaiser et al. (1992) reviewed the legal and institutional barriers to water marketing in Texas. They stated the following finding:

> "Texas surface water law permits the reallocation of water through market based transfers and contains few major obstacles to marketing. One major obstacle is the no-injury rule. Water transfers involving a change in place, purpose, time of use, or point of diversion are allowed provided that the change does not impair (no-injury) existing uses. The most viable solution to the no-injury rule is to limit the amount of water transferred to that consumptively used during the previous 5 years."

Rice (1993) provides an evaluation of potential water lost by evaporation from free-water surface or evapotranspiration from vegetation or soil. Rice (1993) correctly points out that the determination of water consumptively used depends heavily on the judgement of the investigator. There are many methods for measuring evapotranspiration and for estimating evapotranspiration using historical climatic data. This manual is one method by which parties in the transfer of water can make a first estimate on the magnitude of water consumptively used from a water right. Average annual evapotranspiration is a good estimate for evapotranspiration during the previous 5 years, assuming irrigation and management practices are such that adequate water has been applied to achieve the average annual evapotranspiration.

Evapotranspiration from Wetland Systems

Constructed wetland systems continue to gain in popularity. New wetlands are constructed and used for the treatment of wastewater and the replacement of natural wetlands that are unavoidably lost (Mitsch and Gosselink, 1993). To properly design constructed wetlands, an estimate of water requirements is necessary. Evapotranspiration from the wetlands is a major component of the water requirements.

Variation in Evaporating Surfaces

The surfaces of wetlands vary from open water to very low vegetation (duckweed) or to tall rank growing vegetation (cattails). These different surfaces cause a change in both the albedo (amount of solar radiation reflected from the surface) and the rate of vapor transfer from the evaporating surface. The average albedo for a water surface is 0.06, and thus the water absorbs 94 percent of the incoming solar radiation. This compares to an average albedo of 0.25 for crops in general (Brutsaert, 1982).

The rate of vapor transfer from the evaporating surface is affected by whether the evaporating surface is rough or smooth. Smooth surfaces have lower transfer rates than do rough surfaces. This fact is taken into consideration with the aerodynamic resistance term, r_a. The term r_a is a function of the height of the vegetation, or the surface roughness. Using this fact, the difference in albedo between a water surface and green plant material, and measured ET rates for some wetland vegetation, one can infer appropriate ranges of K_{cb} values for various wetland plants.

It is also clear that even aquatic macrophytes have stomatal resistance. Measurements by Abtew et al. (1995) and Anderson and Idso (1987) have found that stomatal resistance will reduce ET rates for large stands of some aquatic macrophytes below that experienced for free-water evaporation.

Duckweed

According to Doorenbos and Pruitt (1977), free-water evaporation is between 1.1 and 1.2 times ET_o (K_{cb} is between 1.1 and 1.2). Both a water surface and clipped grass are relatively smooth surfaces. The increased evaporation for the water is due primarily to the low albedo and the increase in absorption of incoming solar radiation.

The above comparison is important when estimating the K_{cb} value for a plant such as duckweed. Duckweed, during periods of high wind speeds and in large unprotected ponds, will bunch up leaving 50 percent or more of the surface as open water. During periods of low wind speeds or when protection from the wind is available, duckweed will have essentially 100 percent cover of the water surface. The albedo for duckweed, because it is a green plant, would be near 0.25. Furthermore, the surface roughness for duckweed when fully covering the surface should be lower than clipped grass. Therefore, the average K_{cb} value for duckweed should be between 1.15 and 1.00. Doorenbos and Pruitt (1977) estimated K_{cb} for duckweed to be 1.05. This appears to be a reasonable compromise. If one were certain that duckweed occupied 100 percent of the surface of the water, then a K_{cb} of 0.9 to 0.95 would be appropriate.

Cattails

In Texas most of the cattails are located in isolated stands (making them subject to the clothesline effect) along the banks of streams, lakes, ponds, ditches, and marshes. Because these stands are isolated, the cattails are exposed to different heat, air movement, and vapor exchange than a typical large field (Allen et al., 1992). Adjacent areas often provide a dry fetch. Consequently, these isolated stands have high rates of evapotranspiration compared to free-water evaporation or grass reference evapotranspiration. Anderson and Idso (1987) reported ratios of ET_{crop} to free-water evaporation ranging from 2 to 5.

Allen et al. (1992) appear to provide the most reasonable set of crop coefficients for cattails where lysimeters were used to measure ET. The lysimeters were located near an irrigation ditch and surrounded by irrigated pasture. They reported the crop coefficients based on an alfalfa reference. The alfalfa reference crop coefficient was changed to a grass crop coefficient by dividing by 1.2, a ratio of ET_r to ET_o as determined by comparing the ET from grass and alfalfa lysimeters (Jensen et al., 1990). The coefficients developed by Allen et al. (1992) are presented in Table 27.

Abtew et al. (1993) used lysimeters to measure ET of cattails located in a large cattail marsh. The site was in the Everglades Nutrient Removal Project site (26° 38' Latitude and 80° 25' Longitude). Abtew et al. (1993) calibrated the canopy resistance and aerodynamic resistance for cattails that are vegetation and site specific parameters. With these two parameters, one can estimate ET_{crop} using the Penman-Monteith equation.

Table 27.- Basal Grass Crop Coefficients for Cattails and Bulrushes

Growth Stage	K_{cb} for Cattails	K_{cb} for Bulrushes
Last Killing Frost in Spring	1.2	1.2
Beginning of Maximum Vegetation *	1.9	2.1
Beginning of Senescence And Decline	1.9	2.1
First Killing Frost	0.5	0.5

* This is estimated to be approximately 60 days from initiation for growth. Allen et al. (1992) reported the ratio of the leaf area index to height of plant to be 8.5 ft^{-1} at the beginning of the maximum vegetation growth stage for cattails and 9.2 ft^{-1} for bulrushes.

When comparing the stomatal resistance and aerodynamic resistance of cattails to alfalfa, the stomatal resistance for cattails is greater, but only by a small amount. Abtew et al. (1993) gave the canopy resistance, r_c, as 15.2 s/ft for cattails, while Jensen et al. (1990) gave r_c as 13.5 s/ft for alfalfa. Cattails generally measure 3 ft or greater in height, while the reference height for alfalfa is 1.5 ft. Therefore, the aerodynamic resistance for cattails will generally be smaller than that for alfalfa causing greater ET. With the comparative calculations and other considerations, it appears a K_{cb} value of 1.4 is appropriate for full canopy and vigorous growth. This is approximately the ratio of ET_{crop} to free-water evaporation found by Anderson and Idso (1987). The K_{cb} values after the last killing frost in the spring and for the first killing frost are estimated to be the same as for the isolated stands as presented above in Table 27. Sugarcane, a very similar plant to cattails in terms of surface geometry, has a recommended K_{cb} value of 1.3 for the peak month compared to 1.4 for extensive areas of cattails (SCS, 1993).

Bulrushes

Allen et al. (1992) also presented K_{cb} values for isolated stands of bulrushes. Shown in Table 27 are the K_{cb} values for the different growth stages. The data for the bulrushes were collected in the same area as the ET data for the isolated stands of cattails as described above. The ET rates are about 10 percent greater than for cattails because of the greater height of the vegetation. There appears to be an absence of research on the ET rates for bulrushes in large marshes or other similar areas. A K_{cb} value of 1.4, similar to cattails; is recommended for a fully established site with an extensive area of bulrushes.

Water Fern and Water Lily

Water fern and water lily have planate leaves that float on the water surface. Anderson and Idso (1987) found that the ratio of ET_{crop} to free-water evaportion was 0.9. It appears that free-water evaporation is about 10 percent greater than ET_o. This is based on K_{cb} values reported by Doorenbos and Pruitt (1977) and on comparing the calculated free-water evaporation and ET_o with similar climatic data using the methods presented in this manual. Therefore, the recommended K_{cb} value for water fern and water lily would be 1.0. Anderson and Idso (1987) stated the water fern and water lily displayed stomatal regulation. Thus, with the greater albedo than water and stomatal resistance, the ET rates for water fern and water lily should be less than the free-water evaporation rates.

Water Hyacinths

Anderson and Idso (1987) measured water use by water hyacinths and found relatively short plants (0.2 - 1.2 ft) had a K_{cb} of 1.0. The water hyacinths had a relatively extensive canopy, but little additional advective energy due to peripheral exposure of the canopy. For tall water hyacinths (2.0 - 2.7 ft), the measured K_{cb} was 1.5. This is approximately a 40 percent greater water loss rate than for free-water evaporation. The atmospheric turbulence is caused by the tall plants thus causing the peripheral area to have greater exposure to advective energy. For water hyacinths covering extensive surfaces, a K_{cb} value of 1.2 is recommended. This is based on a decrease in aerodynamic resistance caused by the height of the plants.

Estimating Water Use by Wetland Ponds

The water use by a wetland pond can be determined using a simple water balance. The general equation is:

$$Inflow = outflow + ET + precipitation + seepage \qquad (25)$$

where

Inflow = the water that must be supplied to maintain the water at a given level (ft^3/day)
Outflow = the water discharged from pond (ft^3/day)
ET = evapotranspiration occurring in the pond (ft^3/day)
Precipitation = precipitation falling on pond (ft^3/day)

Seepage = water lost due to seepage from the pond (ft^3/day)

The inflow, outflow, and precipitation can be measured. The seepage is generally near zero for constructed wetlands as required by environmental regulations. If necessary, there are procedures for measuring seepage (Huffman and Westerman, 1995). The last remaining term, ET, can be estimated using the information presented above.

The wetland systems are generally small and are not surrounded by other wetlands. Consequently, the wetland ponds are exposed to advective energy from upwind areas (the clothesline effect). When estimating ET for use in Equation 25, the clothesline effect should be accounted for in the calculations. According to Shuttleworth (1993) the depth affected by the clothesline effect is from 5 to 12 ft. Because of the size of most constructed wetland systems, the oasis effect should be taken into consideration especially in arid and semiarid regions of the State. Listed above are the K_{cb} values for isolated stands of plants commonly found in constructed wetlands. Also presented are estimates of K_{cb} values for plants not subject to the clothesline effect. A weighted average can be used to estimate ET_{crop} for isolated wetlands. The equation is:

$$\overline{K}_{cb} = \frac{10 \times W \times K_{cb(clothesline)} + W \times (L - 10) \times K_{cb(normal)}}{W \times L} \qquad (26)$$

where

$\overline{K}_{cb}$ = the weighted value of K_{cb} for the wetland

W = the width of the wetland perpendicular to the predominant wind direction (ft)

L = the effective length of the wetland parallel to the predominant wind direction (ft). (The effective length is the length necessary for W×L to equal the area of the wetland pond system)

$K_{cb(clothesline)}$ = the K_{cb} for isolated stands of the predominant vegetation in the wetland

$K_{cb(normal)}$ = the K_{cb} for the predominant vegetation located in an extensive pond on similar vegetation.

If for a given vegetation, no estimate or measured value exists for K_{cb} for an isolated stand, the value can be estimated. Multiply the K_{cb} for the vegetation representing an extensive stand by 1.1 for vegetation less than 3 ft in height and 1.15 for vegetation over 3 ft in height. This factor was estimated from the relationships for the clothesline effect presented by Doorenbos and Pruitt (1977).

Estimating Water Use by Native Vegetation

There is relatively little information on the water use of native vegetation in comparison to agricultural crops. Furthermore, the data that are available are not in the form that can be transferred either spatially or temporally. Native vegetation, especially riparian vegetation, uses significant amounts of water. Hansen et al. (1980) stated that for every 10 units of water used for irrigation in the western United States, 8 units of water is lost to phreatophytes such as cattails, tules, willows, saltcedar, and cottonwoods. Vegetation such as saltcedar and honey mesquite are an introduced species that have become vigorous competitors for our limited water resources.

Riparian Plants

Riparian vegetation is that vegetation in the riparian zone of streams. The roots of riparian vegetation generally extract water from the vadoze zone immediately above the water table. Many of the plants are considered phreatophytes or water-loving plants. Water uses by phreatophytes are generally high with water use increasing as the depth to the water table decreases. In the western United States, there are 80 species of phreatophytes and they occupy an estimated 17 million acres (Burgy et al., 1967). Burgy et al. (1967) stated that these phreatophytes consume approximately 25 million ac-ft of water annually.

Riparian zones are generally very productive because of the water availability next to streams. The vegetation provides habitat for wildlife and shading for water in smaller streams. However, the lack of heavy grazing and the advent of introduced species such as saltcedar has changed the type of vegetation and increased the area occupied by phreatophytes. The return flows from irrigation have provided a dependable water supply and have contributed to the expansion of woody species (Horton, 1972).

Saltcedar

Saltcedar (Tamarix pentandra) is one of the most widespread and heavy users of water. Evapotranspiration rates were measured in two studies that appear to be applicable to Texas conditions. There is a study on the Colorado river near Blythe, California (Gay and Hartman, 1982) and a study on the Pecos River near Artesia, New Mexico (Weeks et al., 1987). The study by Gay and Hartman (1982) provides guidance for estimating saltcedar ET_{crop} in South Texas and especially along the Lower Rio Grande

Valley, while the study by Weeks et al. (1987) provides guidance for estimating saltcedar ET_{crop} for West Texas.

Gay and Hartman (1982) measured ET_{crop} for one year to be 68.0 inches near Blythe, California. Daily rates as high as 0.50 inches per day were measured. They did not provide any estimation for ET_o. However, ET_o was measured at Blythe for several years immediately following the experiment and one can infer with some confidence that the average ET_o at Blythe would be a good estimate for ET_o during the time of the study. The average annual ET_o at Blythe was 72.7 inches for three years following the experiment. If we apply Equation 5, an annual value for K_c would be 0.93. The growing season was reported by Gay and Hartman (1982) to be from March 23rd through November 11th. The K_c for the growing season (March 23rd through November 11th) was estimated to be 1.14. Killing frosts seldom occur in the region. Average temperatures for Blythe are shown in Figure 50. The ET_{crop} includes direct evapotranspiration during the dormant season. Note that measurements were taken in a very dense grove of saltcedar and the water table depth was approximately 10 ft.

On the Pecos River, Weeks et al. (1987) measured ET_{crop} to be 30.3 to 42.1 inches for saltcedar for one year. The growing season was reported as April 1st through November 15th. The ET for the non-growing season was arbitrarily set at 40 percent of ET_o. For the experiment, an alfalfa reference ET was used. The alfalfa reference crop evapotranspiration (ET_r) was changed to ET_o by dividing by 1.2, a ratio of ET_r to ET_o as determined by comparing the ET from grass and alfalfa lysimeters (Jensen et al., 1990). The annual ET_o was 57.5 inches. Using Equation 5, the annual K_c values would be 0.53 to 0.73. The K_c values for the growing season (April 1st through November 15th) were 0.56 to 0.83. The average temperatures for Roswell, New Mexico are shown in Figure 51. Four different sites were measured. The site with the highest water use was an old growth site (vegetation height about 16 ft) with a dense growth and a water table of 2 to 3 ft in depth. The site with the lowest ET_{crop} was old growth (vegetation height about 10 ft) with only 80 percent cover and a water table approximately 12 ft in depth. One site with medium ET_{crop} was mowed about 4 years previous to measurement. There was only 50 percent ground cover (vegetation about 8 ft in height) and a water table of 11 ft in depth. A second site with medium ET_{crop} was burned about 8 years before the experiment. The vegetation was dense with a height of 8 ft and a water table depth of 5 to 7 ft.

The variability of saltcedar vegetation and the conditions under which it grows is great. Weeks et al. (1987) state there is no apparent correlation between measured water use and depth to water, plant density, and plant age. Consequently, it is difficult to assign one K_{cb} value to a

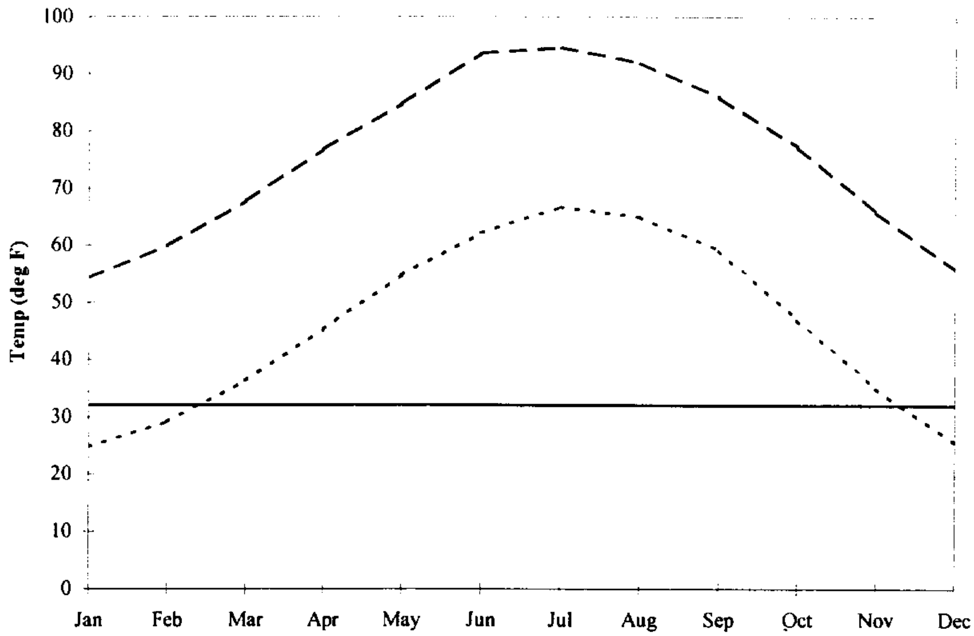


Figure 50.-Mean Monthly Minimum and Maximum Air Temperatures for Roswell, NM.

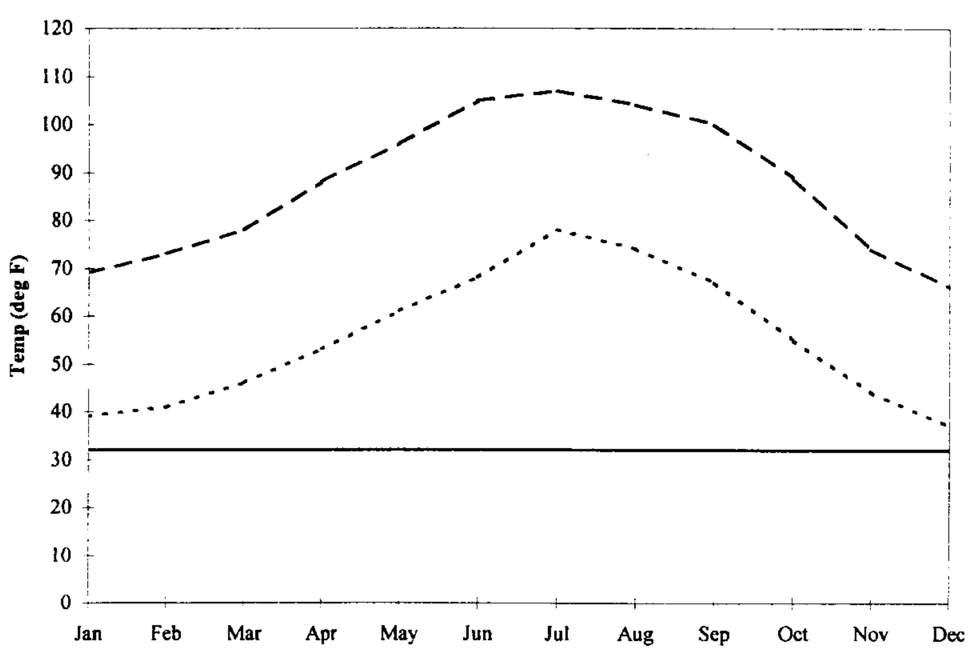


Figure 51.-Mean Monthly Minimum and Maximum Air Temperatures for Blythe, CA.

particular site. The results of the experiments discussed above provide some guidance. Overall, a K_c or K_{cb} of 1.0 may be appropriate for basin-wide estimates. The research by McDonald and Hughes (1968), Robinson and Waananen (1970), and van Hylckama (1974) may be referred to for further information on the ET rates for saltcedar.

Mesquite

Water use by mesquite (honey mesquite) has been studied by several researchers (Weltz and Blackburn, 1995; Levitt et al., 1995; Dugas et al., 1992; Dugas and Mayeus, 1991; Carlson et al., 1990; and Franklin, 1987). However, specific K_{cb} values have not been established for mesquite. It is clear that in a rangeland situation, the normal seasonal ET_{crop} for mesquite is approximately 95 percent of the precipitation (Weltz and Blackburn, 1995; Carlson et al, 1990; and Franklin, 1987). The monthly ET values somewhat mirror precipitation but with a time lag. The research by Weltz and Blackburn (1995) did have measured ET rates for periods of adequate moisture. The ET rates immediately following heavy precipitation events appeared to be 1.2 times ET_o when using the the mean monthly ET_o rates as the estimate for ET_o at the time of the experiment. Franklin (1987) reported daily rates that appear to be greater than mean annual ET_o rates. Note that Cuomo et al. (1992) reported that average daily transpiration of trees at a riparian site (water table within 5 ft of the surface) had transpiration rates 44 percent greater than transpiration rates from non-riparian sites.

For those occasions where honey mesquite has adequate water, such as when located in riparian zones with relatively high water tables or following periods of heavy precipitation, one would expect ET rates to be the same as fruit orchards (see Table 9 for K_{cb} coefficients). Note that Levitt et al. (1995) measured a K_c of 1.56 for a single mesquite tree (Prossopis alba 'Colorado'). Evapotranspiration for a single tree in a container would be expected to be greater than a stand of well-watered trees on rangeland. It does support the potential for mesquite to use water at the rates for a fruit orchard. For estimates of annual water use by mesquite on rangeland, the best estimate appears to be approximately 95 percent of precipitation (Carlson et al., 1990).

Salt Grass

Charles et al. (1987) measured the water use by salt grass, a phreatophyte, in the San Luis Valley in Colorado. They calculated K_c values for grass using an alfalfa reference crop evapotranspiration (ET_r).

The K_c values were changed for use with ET_o by multiplying by a factor of 1.2 (see the discussion above). The K_c values ranged from 0.32 to 0.82 with an average K_c value of 0.70. The low K_c value appears to be a characteristic of the plant rather than water stress. The K_c value, due to the relative dry climate in the San Luis Valley, can be assumed to be the K_{cb} value for the grass.

Pine

Bidlake et al. (1996) investigated ET from native vegetation in West-central Florida. They used Bowen ratio and eddy correlation methods to estimate ET_{crop} for pine flatwoods (Pinus elliottii). The annual ET_{crop} was 41.73 inches. The annual ET_o was calculated to be 71.65 inches giving a K_c value of 0.58. The authors noted that the ET_{crop} was essentially the same as that measured using water-budget studies in similar areas in West-central Florida. Mean annual precipitation is approximately 56 inches with 50 percent of the precipitation occurring from June through September.

Aquatic Macrophytes

Presented above in the section "Estimating Water Use for Wetland Systems" are K_{cb} values for several aquatic macrophytes. The aquatic macrophytes include duckweed, cattails, bulrushes, water fern, water lilies, and water hyacinth.

Range Grasses

The range and pasture lands of Texas have both native and introduced species of grasses. In general, the open range has predominantly native species while the irrigated pastures and revegetated pastures have introduced species.

The grasses, for purposes of estimating ET rates, can be separated into warm-season (C4 metabolism) and cool-season grasses (C3 metabolism). Some common warm-season grasses found in Texas include big bluestem, blue grama, buffalo grass, and weeping lovegrass. Examples of cool-season grasses include smooth brome, Italian ryegrass, and crested wheatgrass. In general, the warm-season grasses have about 20 percent less ET under conditions of adequate water and fertilization.

The annual ET for range grasses is approximately 95 percent of the annual precipitation (Carlson et al., 1990). This will hold true in most parts of Texas because the evapotranspiration potential is much greater than annual precipitation rates. To calculate the ET from day to day or even month to month when precipitation provides all of the moisture for the grass, is beyond the scope of this manual. Ritchie et al. (1976) provides a procedure for calculating evaporation from native grassland watersheds when annual precipitation is much less than annual potential evapotranspiration.

If the grasses have adequate moisture for vigorous growth, then one can generalize about the appropriate K_{cb} values to use to estimate ET_{crop}. It is possible to group all species into two groups—cool-season and warm-season grasses. For grasses used in pasture (no specification was made on the specie(s) of grass, Doorenbos and Pruitt (1977) recommended a K_{cb} value of 0.95 for humid conditions and light to moderate winds, and a K_{cb} value of 1.0 for dry conditions and light to moderate winds. Based on ET data for turfgrasses where relatively good measurement of ET has been made for both warm-season and cool-season grasses, it is recommended that the K_{cb} values provided by Doorenbos and Pruitt (1977) be decreased by 0.1 for warm-season grasses and increased by 0.1 for cool-season grasses. One should realize that there are many unknowns associated with the above estimated K_{cb} values.

Chapter 7

Auxiliary Information

Water Stress

This manual provides estimates for ET for well-watered crops that are actively growing and have adequate nutrients and environmental conditions for growth. There are some situations where one may want to estimate ET for a crop that is water stressed. Equation 6 provides the relationship to adjust the crop coefficient, K_c.

$$K_c = K_{cb} \times K_s + K_w \qquad (6)$$

where

K_c = the crop coefficient for a particular crop
K_{cb} = the basal crop coefficient for the particular crop
K_s = the factor related to water stress
K_w = factor to account for the increased evaporation from wet soils following rain or irrigation.

There are at least three different models for estimating K_s in the literature. There is the logarithmic model presented by Jensen et al. (1970) and Burman et al. (1983), the linear model proposed by Boonyatharokul and Walker (1979), and the linear model presented by SCS (1993). The SCS (1993) method for drought-sensitive crops is the same model proposed by Boonyatharokul and Walker (1979). The model is:

$$K_s = 1 \qquad \text{for AW} \geq 50\,\% \text{ for drought sensitive crops} \qquad (27)$$

$$K_s = \frac{1}{0.5}\left(\frac{D_t - D_p}{D_t}\right) \qquad \text{for } K_s \langle 1 \text{ for drought sensitive crops} \qquad (28)$$

where

K_s = the factor related to water stress
AW = available soil water (in.)
D_t = total available soil water in the root zone (in.)
D_p = depleted available soil water from entire root zone (in.)

The total available water is defined by the following equation:

$$D_t = R_d\left(\frac{\Theta_{fc} - \Theta_{pwp}}{100}\right) \quad (29)$$

where

D_t = total available soil water in the root zone (in.)
R_d = root zone depth (in.)
Θ_{fc} = volumetric water content at field capacity (percent)
Θ_{pwp} = volumetric water content at the permanent wilting point (percent)

For further definition of terms, the reader is referred to the glossary on page 220.

The procedure by Boonyatharokol and Walker (1979) did not make a distinction between drought sensitive crops and drought-tolerant crops as did the above procedure by the SCS (1993) given above. The SCS (1993) did not provide any guidance as to which crops are drought sensitive or drought-tolerant. The modified formula for drought-tolerant crops is:

$$K_s = 1 \qquad \text{for AW} \geq 25\,\% \text{ for drought-tolerant crops} \quad (30)$$

$$K_s = \frac{1}{0.25}\left(\frac{D_t - D_p}{D_t}\right) \qquad \text{for } K_s \langle\, 1 \text{ for drought-tolerant crops} \quad (31)$$

where

K_s = the factor related to water stress
AW = available soil water (in.)
D_t = total available soil water in the root zone (in.)
D_p = depleted available soil water from entire root zone (in.)

Research by Gardner and Hillel (1962) indicates the model described above is valid for bare soil. Similarly, Gardner and Ehlig (1963) found the above model valid for plants.

Stegman et al. (1983) provided some insight into whether a crop is drought-tolerant or drought-sensitive by providing the allowable root zone depletion for several major crops. The allowable root zone depletion is the D_p that can occur before there is any significant reduction in yield. The implied assumption is that ET rates remain at or near potential when yields are at or near maximum. Shown in Table 28 are the allowable root zone water depletion levels for several crops :

Table 28.- Allowable Root Zone Water Depletion Between Irrigations For Maximum Yield Under Non-Automated Irrigation Systems

Crop	Available Water Depletion (percent)	Root Zone Depth Normally Irrigated in Deep Soils (cm)
Alfalfa	30 - 50	120 - 180
Beans, dry	50 - 70	60 - 90
Corn	40 - 60	75 - 120
Cotton	50 - 65	90 - 120
Deciduous fruit	50 - 70	120 - 180
Potatoes	25 - 50	60 - 90
Sugar beet	30 - 60	90 - 120
Grain sorghum	50 - 70	90 - 120
Soybean	50 - 60	60 - 90
Wheat	50 - 70	90 - 120
Vegetable crops	25 - 50	60 - 120

Unless one has information to the contrary, it is recommended to use the K_s for drought sensitive crops. One might reason that native vegetation would be drought tolerant. However, most phreatophytes are probably drought sensitive.

Salinity Control

All irrigation water contains salts and these salts remain in the soil after evapotranspiration occurs. To maintain the salt balance in the soil (no increase in the amount of salt in the soil), the salts must be flushed or leached below the root zone. In many cases, the leaching requirements are met by unavoidable deep percolation losses during irrigation (Ayers and Westcot, 1976). Keller and Bliesner (1990) computed the leaching requirement for sprinkle and surface irrigation by:

$$LR = \frac{EC_w}{5EC_e - EC_w} \qquad (32)$$

where

LR = leaching requirement ratio for sprinkle or surface irrigation (decimal)
EC_w = electrical conductivity of the irrigation water (mmhos/cm)
EC_e = estimated electrical conductivity of the average saturation extract of the soil root zone profile for an approximate yield reduction (mmhos/cm)

The EC_e is generally taken as the soil salinity, which the relative yield of a crop will be reduced by 10 percent. When EC_e is allowed to become greater than the maximum allowable for zero reduction in relative yield, the EC of the drainage water percolating below the root zone is greater, but less leaching water is required. The soil in the top portion of the root zone is properly leached even for an EC_e resulting in a 10 percent reduction in relative crop yield. Shown in Table 29 are values of EC_e for zero and 10 percent reduction in relative crop yield.

Once the leaching requirement is determined, the gross depth of irrigation is adjusted. There are several procedures for adjusting the gross depth. The SCS (1993) has a relatively precise procedure that takes into consideration such factors as average annual surface runoff as a result of excess precipitation, average surface evaporation in the nongrowing season, and average annual precipitation as well as crop evapotranspiration (ET_{crop}).

Leaching Requirement (LR) ≤ 0.1

For LR ≤ 0.1, the unavoidable deep percolation losses caused by less than the perfect application of water normally meets the leaching requirement. The gross depth of water needed is determined by dividing the

Table 29.-Values of estimated electrical conductivity of the average saturation extract (EC_e) for zero crop reduction and 10 percent crop reduction (Ayers and Westcot, 1976)

Crop	EC_e for zero crop reduction (mmhos/cm)	EC_e for 10% crop reduction (mmhos/cm)
	Field Crops	
Barley	8.0	9.9
Cotton	7.7	9.6
Sugarbeet	7.0	8.7
Wheat	6.0	7.4
Soybean	5.0	5.5
Sorghum	4.0	5.1
Peanut	3.2	3.5
Rice	3.0	3.8
Corn	1.7	2.5
Broadbean	1.6	2.6
Cowpea	1.3	2.0
Beans	1.0	1.5
	Fruit Crops	
Grapefruit	1.8	2.4
Orange	1.7	2.3
Lemon	1.7	2.3
Apple	1.7	2.3
Pear	1.7	2.3
Peach	1.7	2.2
Apricot	1.6	2.0
Grape	1.5	2.5
Strawberry	1.0	1.3
	Vegetable Crops	
Beets	4.0	5.1
Broccoli	2.8	3.9
Tomato	2.5	3.5
Cucumber	2.5	3.3
Cantaloupe	2.2	3.6
Spinach	2.0	3.3
Cabbage	1.8	2.8
Potato	1.7	2.5
Sweet Corn	1.7	2.5
Sweet Potato	1.5	2.4
Pepper	1.5	2.2
Onion	1.2	1.8
Carrot	1.0	1.7
Beans	1.0	1.5

Table 29.-Values of estimated electrical conductivity of the average saturation extract (EC_e) for zero crop reduction and 10 percent crop reduction (Ayers and Westcot, 1976) (continued)

Crop	EC_e for zero crop reduction (mmhos/cm)	EC_e for 10% crop reduction (mmhos/cm)
	Forage Crops	
Tall Wheat Grass	7.5	9.9
Wheat Grass (fairway)	7.5	9.0
Bermuda Grass	6.9	8.5
Barley (hay)	6.0	7.4
Perennial Rye Grass	5.6	6.9
Harding Grass	4.6	5.9
Tall Fescue	3.9	5.8
Crested Wheat Grass	3.5	6.0
Vetch	3.0	3.9
Sudan Grass	2.8	5.1
Wildrye, b Beardless	2.7	4.4
Alfalfa	2.0	3.4
Lovegrass	2.0	3.2
Corn (forage)	1.8	3.2
Clover, Berseem	1.5	3.2

net depth of water required to bring the soil moisture in the root zone up to the desired level by the water application efficiency of the irrigation system. The equation as given by Keller and Bliesner (1990) is:

$$d = \frac{d_n}{EA} \cdot 100 \quad (33)$$

where

d = the gross depth of water per irrigation application (in.)
d_n = the net depth of water application needed to meet consumptive use requirements or the desired increase in moisture content of the root zone (in.)
EA = the water application efficiency of the irrigation system (percent).

Equation 33 in essence does not add any additional water for the purpose of leaching excess salt from the root zone.

Leaching Requirement (LR) > 0.1

When LR is greater than 0.1, additional water must be applied to the soil above that required to bring the root zone to the desired moisture content. The equation given below takes into consideration that leaching depth provided by the unavoidable deep percolation losses. The equation as given by Keller and Bliesner (1990) is:

$$d = \frac{0.9d_n}{(1.0 - LR)EA/100} \quad (34)$$

d = the gross depth of water per irrigation application (in.)
d_n = the net depth of water application needed to meet consumptive use requirements or the desired increase in moisture content of the root zone (in.)
EA = the water application efficiency of the irrigation system (percent)
LR = leaching requirement ratio for sprinkle or surface irrigation (decimal).

If the net depth of leaching provided by precipitation can be determined, the amount can be subtracted from the "d" or the gross depth of water per irrigation application. The depths d and d_n can be determined per irrigation or can be determined per irrigation season. The leaching does not necessarily need to occur during each irrigation, but can occur any time that is convenient during the year.

Irrigation Efficiency

In Texas, approximately 80 percent of all water that is consumptively used is due to the irrigation of crops and turfgrasses. In terms of withdrawal from water sources, irrigation accounts for approximately 65 percent of all withdrawals. Irrigation efficiencies and evapotranspiration are two parameters that are used to determine the amount of withdrawal and amount of water consumptively used by irrigated crops and turfgrasses.

First, evapotranspiration estimates are used to determine the net irrigation requirement for a crop. According to Pair et al. (1983), the following relationship is used to determine net irrigation:

$$I_{net} = W_{et} + W_l - W_s - R_e \tag{35}$$

where

I_{net} = seasonal net irrigation (in.)
W_{et} = the total seasonal evapotranspiration (in.)
W_l = the leaching requirement (in.)
W_s = the water stored in the soil during the off-season (in.)
R_e = the effective precipitation during the growing season (in.).

Once the net irrigation is determined, the gross depth of water needed must be estimated by applying one or more different efficiencies. There are, however, various efficiency terms applied to irrigation systems in the literature and no single definitive reference for the definition of terms. The three most reliable sources appear to be SCS (1993), Cuenca (1989), and Hoffman et al. (1990). The definitions provided below do not represent all the irrigation efficiency terms, but those terms most used in planning water resource projects.

In general two or more efficiency terms are needed to describe an irrigation system. Cuenca (1989) listed four different efficiencies that should be applied to calculating the gross amount of irrigation that must be diverted from a water surface. Several irrigation efficiency terms commonly used to evaluate irrigation systems and to determine the volume of water needed for irrigation purposes are given below.

Extraction Efficiency

$$E_x = \frac{V_{distsys}}{V_{extract}} 100 \qquad (36)$$

where

E_x = extraction efficiency (Cuenca, 1989) (percent)
$V_{distsys}$ = volume delivered to distribution system (canal or pipeline) (ac-ft)
$V_{extract}$ = volume extracted from supply (well, reservoir, or stream) (ac-ft)

Conveyance Efficiency

$$E_c = \frac{V_{app-dev}}{V_{distsys}} 100 \qquad (37)$$

where

E_c = conveyance efficiency (Cuenca, 1989) (percent)
$V_{app-dev}$ = volume of water delivered to application devices (sprinkler, furrow system, etc.) (ac-ft)
$V_{distsys}$ = volume delivered to distribution system (canal or pipeline) (ac-ft)

Water Application Efficiency

The water application efficiency is the most frequently used irrigation efficiency measurement. Water application efficiency, EA, is defined by the SCS (1993) as "the ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of irrigation water applied, expressed as a percentage." The water application efficiency equation is:

$$EA = \frac{V_{root-zone}}{V_{app-dev}} 100 \qquad (38)$$

where

EA = water application efficiency (SCS, 1993) (percent)

V_{root_zone} = volume of water stored in the root zone (ac-ft)
$V_{app\text{-}dev}$ = volume of water delivered to application devices (sprinkler, furrow system, etc.) (ac-ft)

Water losses could include the following quantities: direct evaporation (spray irrigation), wind drift off the field (spray irrigation), evaporation from soil surface, direct runoff from field, and deep percolation below root zone. It is generally agreed that evaporation from the plant surfaces is beneficial use of water and should not be considered a loss.
The above equation, by definition, is the same as the "distribution pattern efficiency" term presented by Cuenca (1989).

Irrigation Efficiency

The On-Farm Irrigation Committee of the American Society of Civil Engineers, Irrigation and Drainage Division (ASCE, 1978) proposed an irrigation efficiency term. ASCE (1978) defined irrigation efficiency as the ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied to the field or system. The irrigation efficiency equation is:

$$IE = \frac{V_b}{V_a} \times 100 \qquad (39)$$

where

IE = the irrigation efficiency (percent)
V_b = the volume or depth of water beneficially used (ac-ft)
V_a = the volume or average depth of water applied to the field (ac-ft).

The volume of water beneficially used is often difficult to determine. In general, beneficially used water includes water used for satisfying the soil moisture deficit, salt leaching, frost protection, crop cooling, and pesticide and fertilizer applications.

Water Storage Efficiency

One could apply a small amount of water to a field and achieve an EA of 100 percent. However, the needs of the crop would not be met. The water storage efficiency is a measure of an irrigation system's ability to replace water in the root zone. The water storage efficiency, ES, is defined as the water stored in the root zone during the irrigation divided by water needed in the root zone prior to the irrigation (Hansen et al., 1980). The water storage efficiency is:

$$ES = \frac{V_{srs}}{V_{nrs}} \times 100 \tag{40}$$

where

ES = the water storage efficiency (percent)
V_{srs} = the volume or average depth of water stored in the root zone during the irrigation (ac-ft)
V_{nrs} = the volume or average depth of water needed in the root zone to bring the root zone up to field capacity (ac-ft)

Christiansen's Uniformity Coefficient

Christiansen's uniformity coefficient (UCC) was developed to measure the uniformity of application of water over a field. It is most commonly used for sprinkler irrigation systems. While there are other uniformity coefficients, the most widely used uniformity coefficient is still the UCC. UCC is defined as:

$$UCC = 100\left[1 - \frac{\sum_{i=1}^{n} |x_i - \bar{x}|}{n \times \bar{x}}\right] \tag{41}$$

where

UCC = Christiansen's uniformity coefficient (Cuenca, 1989) (percent)
x_i = the catch or depth of water at individual locations (in.)
$\bar{x}$ = the average catch or depth of water of all locations (in.)
n = the number of locations where measurements were made.

A UCC of 100 percent would indicate perfect distribution. Seventy percent is the minimum acceptable for agricultural sprinkler systems.

The SCS (1993) presented an equation that estimates EA as a function of UCC and a term, A_u. The term A_u is the fraction of the field that is deficiently irrigated. Water is not equally distributed on a field. If an average of 1 inch of water is applied, approximately 50 percent of the field would receive more than 1 inch in depth, and approximately 50 percent of the field would receive less than 1 inch in depth. One could apply more than 1 inch so that, for example, 85 percent of the field would receive 1 inch or more of water application. In such a case, the fraction of the field receiving deficit irrigation or less than the desired 1 inch would be 15 percent—A_u would thus be 15 percent.

The equation relating UCC and A_u to EA is:

$$EA = 100[1 - (1.25 - 0.0125UCC)(3.634 - 1.123A_u^{0.3} + 0.003A_u^{1.233})] \quad (42)$$

where

EA = the water application efficiency (percent)
UCC = Christiansen's uniformity coefficient (percent)
A_u = the fraction of the field that is deficiently irrigated (percent).

Effective Precipitation

In the planning of water supply systems where irrigation is involved, precipitation must be taken into consideration. In the calculation of net irrigation requirement, effective precipitation is considered as follows:

$$I_{net} = W_{et} + W_l - W_s - R_e \tag{43}$$

where

I_{net} = seasonal net irrigation (in.)
W_{et} = the total seasonal evapotranspiration (in.)
W_l = the leaching requirement (in.)
W_s = the water stored in the soil during the off-season (in.)
R_e = the effective precipitation during the growing season (in.).

Effective precipitation is defined as "precipitation falling during the growing period of the crop that is available to meet the consumptive water requirements of crops. It does not include precipitation that is lost to deep percolation below the root zone, surface runoff, or evaporation from soil surface" (SCS, 1993). The SCS (1970) published a method to estimate average monthly effective precipitation as a function of mean monthly ET_{crop}, mean monthly precipitation, and net depth of water depletion in the soil. Cuenca (1989) developed two regression equations that allow the calculation of effective precipitation mathematically. The equations are as follows:

$$f(D) = 0.526 + 0.302D - 0.06D^2 + 3.977 \times 10^{-3} \times D^3 \tag{44}$$

$$P_{ef} = f(D)\left[0.7074 P_t^{0.824} - 0.11535\right] \times 10^{0.02426\, ET_{crop}} \tag{45}$$

where

P_{ef} = effective precipitation (in./mon)
D = normal depth of irrigation prior to irrigation (in.)
f(D) = function to account for depth of soil moisture depletion other than 3 inches
P_t = total precipitation (in./mon)
ET_{crop} = mean crop evapotranspiration (in./mon)

Note that the value of effective precipitation is limited to the lesser of P_t, ET_{crop}, or P_{ef} as calculated using the above equations.

As one might suspect, estimating effective precipitation is more complex than the simplified procedure presented above. Factors such as soil intake rates and rainfall intensities are not used in Equation 45. Effective precipitation also can be changed such as that which occurs with the use of furrow dikes—a practice common in West Texas. There would also appear to be significant differences in effective precipitation when applied to rice paddies versus row crops in Central Texas.

For greater insight into the determination of effective precipitation, readers are referred to the Food and Agriculture Organization of the United Nations publication "Effective Rainfall in Irrigated Agriculture" (Dastane, 1974). This publication details the measurement and estimation of effective precipitation. The Soil Conservation Service method for estimating effective precipitation (Equation 45) appears adequate for planning when dealing with monthly values of precipitation, evapotranspiration, and irrigation water requirements.

References

Abtew, W., S. Newman, K. Pietro, and T. Kosier. (1995). "Canopy resistance studies of cattails." Transactions of the American Society of Agricultural Engineers, 38 (1), 113 - 119.

Allen, J. B. (1965). "An analysis of evaporation at Lake Hefner, 1965 - 1966, based on the water budget, energy budget, and evaporation tanks." Ph.D. dissertation, Oklahoma State University, Stillwater, OK.

Allen, R. G., J. H. Prueger, and R. W. Hill. (1992). "Evapotranspiration for isolated stands of hydrophytes: cattails and bulrush." Transactions of the American Society of Agricultural Engineers, 35 (4), 1191 - 1198.

American Society of Agricultural Engineers. (1985). Proceedings of the National Conference on Advances in Evapotranspiration, ASAE, St. Joseph, MI.

Anderson, M. G., and Idso, S. B. (1987). "Surface geometry and stomatal conductance effects on evaporation from aquatic macrophytes." Water Resources Research, 23 (6), 1037 - 1042.

Aronson, L. J., A. J. Gold, R. J. Hull, and J. L. Cisar. (1987). "Evapotranspiration of turfgrass." Agronomy Journal, 79, 901 - 905.

ASCE. (1978). "Describing irrigation efficiency and uniformity." Journal of the Irrigation and Drainage Division, ASCE, 104(1), 35 - 41.

Beard, J. B. 1973. Turfgrass: Science and Culture. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Bidlake, W. R., W. M. Woodham, and M. A. Lopez. (1996). "Evapotranspiration from areas of native vegetation in West-Central Florida." U.S. Geological Survey Water Supply Paper 2430, United States Government Printing Office, Washington, D.C.

Biran, L., B. Bravdo, I. Bushkin-Harav, and E. Rawitz. (1981). "Water consumption and growth rate of 11 turfgrasses as affected by mowing height, irrigation frequency, and soil moisture." Agronomy Journal, 73, 85 -90.

Boonyatharokul, W., and Walker, W. R. (1979). "Evapotranspiration under depleting soil moisture." Journal of the Irrigation and Drainage Division, ASCE, 105(4), 391 - 402.

Borrelli, J., L. O. Pochop, W. R. Kneebone, I. L. Pepper, R. E. Danielson, W. E. Hart, and V. B. Younger. (1981). "Blaney-Criddle coefficients for western turf grasses." Journal of the Irrigation and Drainage Division, ASCE, 107(4), 333 - 341.

Brutsaert, Wilfried. (1982). Evaporation into the Atmosphere. D. Reidel Publishing Company, Boston.

Budyko, M. I. (1974). Climate and life. Academic Press, New York.

Burgy, R. H., J. E. Fletcher, and A. L. Sharp. (1967). "Watershed management." Irrigation of agricultural lands, R. M. Hagan, H. R. Haise, and T. W. Edminster, eds., American Society of Agronomy, Madison, WI, 1089 - 1104.

Calder, I. R., and Neal, C. (1984). "Evaporation from saline lakes: Combination equation approach." Journal of Hydrological Sciences, 29(1), 89 – 97.

Camp, C. R., E. J. Sadler, and R. E. Yoder. (1996). "Evapotranspiration and irrigation scheduling." Proceedings of the International Conference, ASAE, San Antonio, TX.

Carlson, D. H., T. L. Thurow, R. W. Knight, and R. K. Heitschmidt. (1990). "Effect of honey mesquite on the water balance of Texas rolling plains rangeland." Journal of Range Management, 43(6), 491 - 496.

Carrow, R. N. (1995). "Drought resistance aspects of turfgrasses in the Southeast: Evapotranspiration and crop coefficients." Crop Science, 35, 1685 -1690.

Charles, F. L., W. C. Bausch, and J. A. Morgan. (1987). "Evapotranspiration of phreatophytes in Colorado's San Luis Valley." Paper No. 87-2117, 1987 Summer Meeting of the American Society of Agricultural Engineers, Baltimore, MD.

Crow, F. R., J. B. Allen, W. E. Fry, and A. L. Mitchell. (1967). "An investigation to evaluate specific techniques for determining the effectiveness of monolayer-forming materials in reducing evaporation losses from Lake Hefner." Final Report to US Bureau of Reclamation, Contract No. 14-06-D-5629, School of Agricultural Engineering, Oklahoma State University, Stillwater, OK.

Cuenca, R. H. (1989). Irrigation system design: An engineering approach. Prentice Hall, Englewood Cliffs, NJ.

Cuoma, C. J., R. J. Ansley, P. W. Jacoby, and R. E. Sosebee. (1992). "Honey mesquite transpiration along a vertical site gradient." Journal of Range Management, 45(4), 334 - 338.

Dastane, N. G. (1974). "Effective rainfall in irrigated agriculture." FAO Irrigation and Drainage Paper No. 25, FAO, Rome, Italy.

Doorenbos, J. and Pruitt, W. O. (1977). "Guidelines for predicting crop water requirements." FAO Irrigation and Drainage Paper No.24, 2nd edition, FAO, Rome, Italy.

Duble, R. L. 1988. "Turfgrasses for Texas lawns." L-1865, Texas Agricultural Extension Service, The Texas A&M University System, College Station, TX.

Dugas, W. A., and Mayeux, H. S. (1991). "Evaporation from rangeland with and without honey mesquite." Journal of Range Management, 44(2), 161 - 170.

Dugas, W. A., M. L. Heue, and H. S. Mayeux. (1992). "Diurnal measurements of honey mesquite transpiration using stem flow gauges." Journal of Range Management, 45(1), 99 - 102.

Feldhake, C. M., R. E. Danielson, and J. D. Butler. (1983). "Turfgrass evapotranspiration. I. Factors influencing rate in urban environments." Agronomy Journal, 75(5), 824 - 830.

Franklin, J. D. (1987). "Hydrologic aspects of grass dominated and honey mesquite dominated areas on the rolling plains of Texas." M.S. thesis, Texas A&M University, College Station, TX.

Gardner, W. R., and Hillel, D. I. (1962). "The relation of external evaporative conditions to the drying of soils." Journal of Geophysical Research, 67, 4319 - 4325.

Gardner, W. R., and Ehlig, C. F. (1963). "The influence of soil water on transpiration of plants." Journal of Geophysical Research, 68, 5719 - 5724.

Garrot, D. J., and Mancino, C. F. (1994). "Consumptive water use of three intensively managed bermudagrasses growing under arid conditions." Crop Science, 34, 215 - 221.

Gay, L. W., and Hartman, R. K. (1982). "ET Measurements over riparian saltcedar on the Colorado River." Proceedings of Hydrology and Water Resources in Arizona and the Southwest, 12, 9 - 15.

Gerst, M. D., R. L. Postma, and C. W. Wendt. (1982). "Preliminary evaluations of the performance of home lawn sprinklers." Technical Report No. 82-2, Texas Agricultural Experiment Station, Lubbock, TX.

Gregory, J. M. (1989). "Wind data generation for Great Plains locations." Paper presented at the International Conference of the American Society of Agricultural Engineers, New Orleans, LA, Paper #89-2664.

Hill, R. W. (1994). "Consumptive use of irrigated crops in Utah." Research Report 145, Utah Agricultural Experiment Station, Utah State University, Logan, UT.

Hoffman, G. J., T. A. Howell, and K. H. Soloman. (1990). Management of Farm Irrigation Systems. ASAE, St. Joseph, MI.

Horton, J. S. (1972). "Management problems in phreatophyte and riparian zones." Journal of Soil and Water Conservation, 27(2), 58 - 61.

Huffman, R. L., and Westerman, P. W. (1995). "Estimated seepage losses from established swine waste lagoons in the lower costal plain of North Carolina." Transactions of American Society of Agricultural Engineers. 38(2), 449 - 453.

Itier, B., and Brunet, Y. (1996) "Recent developments and present trends in evaporation research: A partial survey." Evapotranspiration and Irrigation Scheduling, C. R. Camp, E. J. Sadler, and R. E. Yoder, eds., ASAE, St. Joseph, MI,1 - 20.

Jensen, M., E., D. C. N. Robb, and C. E. Franzoy. (1970). "Scheduling irrigations using climate-crop-soil data." Journal of the Irrigation and Drainage Division, ASCE, 96(1), 25 - 38.

Jensen, M. E.(ed.) (1974). "Consumptive use of water and irrigation water requirements." Report of the Technical Committee on Irrigation Water Requirements, ASCE, Irrigation and Drainage Division, New York.

Jensen, M. E. (1983a). Design and operation of farm irrigation systems. ASAE, St. Joseph, MI.

Jensen, M. E. (1983b). "Terminology." Seminar on consumptive use/evapotranspiration problems of water right changes, City of Denver, Denver, CO. December 2.

Jensen, M. E., R. D. Burman, and R. G. Allen. (1990). "Evapotranspiration and irrigation water requirements," ASCE Manual No. 70, ASCE, New York.

Jensen, R. (1997). "Water marketing in Texas/1966." World Wide Web. http://twri.tamu.edu.watertalk.archive/1997.

Jones, F. E. (1992). Evaporation of Water. Lewis Publishers, Chelsea, MI.

Jonish, J., N. Terry, and D. Yoskowitz. (1996). "Water marketing along the Texas Rio Grande." Proceedings of UCOWR, San Antonio, TX.

Kaiser, R. A., F. Boadu, J. Mertes, A. Barnett, and L. M. Phillips. (1992). "Legal and institutional barriers to water marketing in Texas." Technical Report No. 167, Texas Water Resources Institute, The Texas A&M University System, College Station, TX.

Keller, J., and Bliesner, R. D. (1990). Sprinkle and Trickle Irrigation, **avi** Book, Van Nostrand Reinhold, New York.

Kerr, G., L. Pochop, and T. Teegarden. (1996). "Cool-season turfgrass: Estimating water use." Journal American Water Works Association, 88(1), 91 - 96.

Kim, K. S., and Beard, J. B. (1988). "Comparative turfgrass evapotranspiration rates and associated plant morphological characteristics." Crop Science, 28, 328 - 331.

Knapp, H. Vernon, (1990). "Evaporation and transpiration." Handbook of Applied Meteorology, David D. Houghton, ed., John Wiley & Sons, New York, 537 – 554.

Kneebone, W. R., I. L. Pepper, R. E. Danielson, W. E. Hart, L. O. Pochop, and J. Borrelli. (1979). "Water requirements for urban lawns." Project B-036-WYO: Project Completion Report, Office of Water Research and Technology, US Department of the Interior. University of Wyoming, Laramie, WY.

Konstantinow, A. R. (1966). "Evaporation in nature." Israel Program for Scientific Translations, Jerusalem, Israel.

Kopec, D. M., R. C. Shearman, and T. P. Riordan. (1988). "Evapotranspiration of tall fescue." HortScience, 23(2), 300 - 301.

Kopec, D. M., P. W. Brown, C. F. Mancino, and D. C. Slack. (1990). "Developing crop coefficients for desert turfgrass: Calibrating reference ET with turf water use." Proceedings of the 1990 National Irrigation Symposium, Phoenix, AZ.

Lettau, H., and Zabransky, J. (1968). "Interrelated changes of wind profile structure and Richardson number in air flow from land to inland lakes." Journal of the Atmospheric Sciences, 25, 718 - 728.

Levitt, D. G., J. R. Simpson, and J. L. Tipton. (1995). "Water use of two landscape tree species in Tucson, Arizona." Journal of the American Society of Horticulture Science, 120(3), 409 - 416.

Linsley, R. K., M. A. Kohler, and J. L. H. Paulhus. (1975). Hydrology for Engineers. McGraw-Hill, Inc., New York.

Marciano, J. J., and Harbeck, G. E. (1954). "Mass transfer studies." U.S. Geological Survey, Professional Paper No. 269, United States Government Printing Office, Washington, D.C., 46 - 70.

McDonald, C. C., and Hughes, G. H. (1968). "Studies of consumptive use of water by phreatophytes and hydrophytes near Yuma, Arizona." U.S. Geological Survey Professional Paper 486-F, United States Government Printing Office, Washington, D.C.

Mecham, B. Q. (1996). "Scheduling turfgrass irrigation by various ET equations." Evapotranspiration and irrigation scheduling, C. R. Camp, E. J. Sadler, and R. E. Yoder, eds., ASAE, St. Joseph, MI, 245 - 249.

Mohseni-Saravi, M., L. W. Gay, and P. W. Brown. (1996). "Application of Penman's model in the arid environment." Evapotranspiration and irrigation scheduling, C. R. Camp, E. J. Sadler, and R. E. Yoder, eds., ASAE, St. Joseph, MI, 864 - 869.

Morgan, D. L. and Lourence, F. J. (1969). "Comparison between rain gage and lysimeter measurements." Water Resources Research, 5(3), 724 - 728.

Morgan, D. L., W. O. Pruitt, and F. J. Lourence. (1971). "Analysis of energy, momentum, and mass transfers above vegetative surfaces." Final Report No. DA IT061102B53A-17, Department of Water Science and Engineering, University of California, Davis, CA.

National Research Council. (1992). Water transfers in the West. National Academy Press. Washington, D.C.

Nir, D., and Finkel, H. J. (1982). "Water requirements of crops and irrigation rates." Handbook of Irrigation Technology, Vol. 1, H. J. Finkel, ed., CRS Press Inc., Boca Raton, FL, 61 - 78.

Oad, R., and DiSpigna, M. (1966). "Measurement of evapotranspiration in urban landscapes." Evapotranspiration and Irrigation Scheduling, C. R. Camp, E. J. Sadler, and R. E. Yoder, eds., ASAE, St. Joseph, MI, 239 - 244.

Penman, H. L. (1948). "Natural evaporation from open water, bare soil, and grass." Proceedings of the Royal Society, Series A, 193, 120 - 145.

Qian, Y. L., J. D. Fry, S. C. Wiest, and W. S. Upham. (1996). "Estimating turfgrass evapotranspiration using atmometers and the Penman-Monteith model." Crop Science, 36, 699 - 704.

Rich, L. G. (1961). Unit Operations of Sanitary Engineering. John Wiley and Sons, Inc. New York.

Richie, J. T. (1979). "Water management and water efficiencies for American agriculture." Proceedings of the Weather and Agriculture Symposium, University of Missouri Agricultural Experiment Station Publication MX-245, Kansas City, MO, 15 - 42.

Rice, L. (1993). "Evaluating the facts in water right changes." Proceedings of the Management of Irrigation and Drainage Systems: Integrated Perspectives, R. G. Allen, ed., ASCE, New York, 1063 - 1070.

Robinson, T. W., and Waananen, A. O. (1970). "Evapotranspiration by woody phreatophytes in the Humboldt River Valley near Winnemucca, Nevada." U.S. Geological Survey Professional Paper 491-D. United States Government Printing Office, Washington, D.C.

Sacks, L. A., T. M. Lee, and M. J. Radell. (1994). "Comparison of energy-budget evaporation losses from two morphometrically different Florida seepage lakes." Journal of Hydrology, Elsevier, 156, 311 – 334.

Sharif, M. (1989). "Development of a physically exact energy balance method for estimating evaporation from free water surfaces." Ph.D. dissertation, Texas Tech University, Lubbock, TX.

Shuttleworth, W. J. (1993). "Evaporation." Handbook of Hydrology, D. R. Maidment, ed., McGraw-Hill, Inc., New York, 4.1 - 4.53.

Soil Conservation Service. (1993). "Irrigation water requirements." Part 623 National Engineering Handbook, United States Department of Agriculture, Washington, D.C. Soil Conservation Service (1970). Technical Release No. 21, (Revision 2), 1970.

Steiner, J. L., T. A. Howell, and A. D. Schneider. (1989). "Lysimetric evaluation of daily potential evaporation models for grain sorghum." Paper #89-2090, International ASAE Summer Meeting, Quebec City, Canada.

Sutton, O. G. (1934). "Wind structure and evaporation in a turbulent atmosphere." Proceedings of the Royal Society of London, A182, 701 - 722.

Texas Agricultural Statistics Service. (1992). 1991 Texas crop statistics, Texas Department of Agriculture, Austin, TX.

Thornthwaite, C. W., and Holzman, B. (1942). "Measurement of evaporation from land water surfaces." Technical Bulletin No. 817, United States Department of Agriculture.

Tolk, J. A., T. A. Howell, J. L. Steiner, and D. R. Krieg. (1996). "Corn canopy resistance determined from whole plant transpiration." Evapotranspiration and Irrigation Scheduling, C. R. Camp, E. J. Sadler, and R. E. Yoder, eds., ASAE, St. Joseph, MI, 347 - 351.

Unruh, J. B., R. E. Gaussoin, and S. C. Wiest. (1996). "Basal growth temperatures and growth rate constants of warm season turfgrass species." Journal of Crop Science, 36, 997 - 999.

US Geological Survey. (1954). "Water loss investigation - Lake Hefner studies." Technical Report, US Geological Survey Professional Paper No. 270, United States Government Printing Office, Washington, D.C.

van Bavel, C. H. M. (1966). "Potential evaporation: The Combination concept and its experimental verification." Water Resources Research, 2(3), 455 - 467.

van Hylckama, (1974). "Water use by saltcedar as measured by the water budget method." U.S. Geological Survey Professional Paper 491-E, United States Government Printing Office, Washington, D.C.

van Wylen, G. J. (1962). Thermodynamics, John Wiley and Sons, Inc., New York.

Weeks, E. P., H. L. Weaver, G. S. Campbell, and B. D. Tanner. (1987). "Water use by saltcedar and by replacement vegetation in the Pecos River floodplain between Acme and Artecia, New Mexico." U.S. Geological Survey Professional Paper 491-G, United States Government Printing Office, Washington, D.C.

Weltz, M. A., and Blackburn, W. H. (1995). "Water budget for south Texas rangelands." Journal of Range Management, 48(1), 45 - 52.

Wright, J. L. (1981). "Crop coefficients for estimates of daily crop evapotranspiration." Proceedings of the Irrigation Scheduling Conference: Irrigation Scheduling for Water & Energy Conservation in the '80s, ASAE, St. Joseph, MI, 18 - 26.

Wright, J. L. (1982). "New evapotranspiration crop coefficients," Journal of the Irrigation and Drainage Division, ASCE, 108(1), 57 - 73.

Appendix A

Glossary and Symbols

Glossary of Terms

Advection: The horizontal transfer of heat energy by large-scale motions of the atmosphere (Jensen et al., 1990).

Albedo: The ratio of electromagnetic radiation reflected from a soil, crop, or water surface to the amount incident upon it. In practice, the value is applied primarily to solar radiation (Jensen et al., 1990).

Allowable Depletion: The amount, or percentage, of available soil moisture that can be used from the crop root zone without causing plant stresses that reduce yields (SCS, 1993).

Available Soil Moisture: Water in the root zone that can be extracted by plants. The available soil moisture is the difference between field capacity and wilting point (Hill, 1994).

Bowen Ratio: The ratio of energy flux upward as sensible heat to latent energy flux in the same direction (negative when the fluxes are in opposite directions (Jensen et al., 1990).

Clear Day Radiation: Theoretical incoming radiation at earth's surface assuming complete absence of clouds (R_{so}) (Hill, 1994).

Combination Method: One of several forms of methods that use air temperature, relative humidity, solar radiation, and wind speed to predict the evapotranspiration from a reference crop. It is called a combination method because it combines the solar energy with that from advection (SCS, 1993).

Consumptive Use: The total amount of water taken up by vegetation for transpiration or building of plant tissue, plus the unavoidable evaporation of soil moisture, snow, and intercepted precipitation associated with vegetal growth; synonymous with evapotranspiration (Jensen et al., 1990).

Crop Coefficient: Relates evapotranspiration of a given crop at a specific time in its growth stage to a reference evapotranspiration condition. It incorporates effects of crop growth state, plant density, and other cultural factors affecting evapotranspiration, usually expressed or exhibited as a curve or polynomial. The reference condition has been termed "potential" or reference crop" and relates to evapotranspiration of alfalfa or grass, depending upon the research that results in the crop coefficient. The respective "k" or "kc" factor as used in the original and SCS Blaney-

Criddle methods are not based on a reference condition and should only be used with those methods (Hill, 1994).

Crop Growth Stages: Indices used to quantify the phenological development of crops (SCS, 1993).

Crop Irrigation Requirement: The quantity of water, exclusive of effective growing season precipitation, winter precipitation stored in the root zone, or (perhaps) upward water movement from shallow water table, that is required as an irrigation application to meet the evapotranspiration needs of the crop. It also may included water requirements for germination, frost protection, prevention of wind erosion, leaching of salts and plant cooling (Hill, 1994).

Crop Water Use (ET_{crop}): The rate of evapotranspiration by a disease-free crop growing in a large field under nearly optimal agronomic conditions including adequate fertilizer, optimum water availability, plant density, and weed control (SCS, 1993).

Dew Point: The temperature to which a given parcel of air must be cooled at constant pressure and at constant water vapor content until saturation occurs, or the temperature at which saturation vapor pressure of the parcel is equal to the actual vapor pressure of the contained water vapor (Jensen et al., 1990).

Duty of Water: The total volume or irrigation water required to mature a particular type of crop. It includes that portion of consumptive use not satisfied by precipitation, evaporation and seepage from ditches and canals and the water eventually returned to streams by percolation and surface runoff (Hill, 1994).

Effective Cover Date: The time during the growing season when the crop develops enough canopy to fully shade the ground surface so that the ET rate reaches the maximum rate possible for that crop in the existing environmental conditions (SCS, 1993).

Effective Precipitation: The portion of precipitation that remains on the foliage or in the soil that is available for evapotranspiration and reduces the withdrawal of soil water by a like amount (Jensen et al., 1990).

Evaporation: The physical process by which a liquid or solid is transformed to the gaseous state, which usually is restricted to the change of water from liquid to gas (Jensen et al. 1990).

Evaporation Pan: A small pan (48 inch diameter × 10 inches deep) used to estimate the reference crop evapotranspiration rate. Water levels are measured daily in the pan to determine the amount of evaporation (SCS, 1993).

Evapotranspiration: The combined processes by which water is transferred from the earth surface to the atmosphere; evaporation of liquid or solid water plus transpiration from plants (Jensen et al., 1990).

Extraterrestrial Radiation : Solar radiation received "on top of" the earth's atmosphere (Jensen et al., 1990).

Field Capacity: The moisture content of a soil following an application of water and after the downward movement of excess water (from gravitational forces) has essentially ended. Usually it is assumed that this condition is reached about two days after a full irrigation or heavy rain (Hill, 1994).

Fraction of Growing Season: The amount of time that has elapsed since planting, or early growth, relative to the amount of time between planting and physiological maturity or dormancy (SCS, 1993).

Global Radiation: Total of direct solar radiation and diffuse sky radiation received at the earth's surface by a unit horizontal surface (R_s) (Hill, 1994).

Gross Irrigation Water Requirement: The net irrigation water requirement divided by the irrigation efficiency. Sometimes called irrigation requirement (SCS, 1993).

Growing Season: The period that is warm enough for plants to transpire and grow. In the case of annual plants, it approximates the time interval between planting and crop maturity; for perennial crops, it is the period between certain temperature conditions that establish growth and dormancy. This growing season is sometimes restricted to the period between killing frosts (Hill, 1994).

Irrigation Efficiency: The ratio of the average depth of irrigation water that is beneficially used to the average depth of irrigation water applied, expressed as a percentage (SCS, 1993).

Irrigation Scheduling: A process that is repetitively used during the growing season to decide when to irrigate and how much water to apply (SCS, 1993).

Irrigation Water Requirement: The quantity, or depth, of water in addition to precipitation, required to obtain desired crop yield and to maintain a salt balance in the root zone (SCS, 1993).

Langley: The amount of energy (calories) received on a unit surface area (cm^2). This unit is commonly used for recording the amount of solar radiation received on a daily basis (SCS, 1993).

Leaching: The process of water movement through and below the crop root zone by gravitation. It occurs whenever the infiltrated irrigation water and rainfall exceed ET_{crop} and the water storage capacity of the soil profile (SCS, 1993).

Leaching Fraction: That portion of the irrigation water and precipitation entering the soil that effectively flows through and below the crop root zone (SCS, 1993).

Leaching Requirement: That part of the irrigation water and precipitation entering the soil that effectively must flow through and below the crop root zone to prevent the buildup of salinity within the crop root zone. Minimum leaching fraction needed to prevent yield reduction (SCS, 1993)

Leaf Area Index (LAI): The ratio of the amount of leaf area of a crop stand relative to the amount of land area underlying that crop (SCS, 1993).

Long-Wave Radiation: All wave lengths of electromagnetic radiation greater than solar radiation or 3 micrometers.

Lysimeter: A device such as a tank or large barrel that contains a mass of soil and vegetation similar to that in the immediate vicinity, which is isolated hydrologically from its surroundings. It is commonly used in research to determine the water use of various crops in field conditions (Hill, 1994).

Management Allowed Depletion (MAD): The desired soil water deficit, below field capacity, at the time of irrigation (SCS, 1993).

Mean Crop Consumptive Use: The long term average of annual consumptive use rates for the particular crop in question.

Net Back Radiation: The thermal or long wave radiation that is outgoing from the earth's surface (R_b) (Hill, 1994).

Net Clear Day Outgoing Long Wave Radiation: Theoretical outgoing long wave radiation at the earth's surface assuming complete absence of clouds (R_{bo}) (Hill, 1994).

Net Irrigation Requirement: The depth of irrigation water, exclusive of effective precipitation, stored soil moisture, or ground water that is required for meeting crop evapotranspiration for crop production and other related uses. Such uses may include water required for leaching, frost protection (SCS, 1993).

Net Radiation: The difference of the downward and upward solar and long-wave radiation flux passing through a horizontal plane just above the ground surface (Jensen et al., 1990).

Pan Evaporation: Evaporation from a class A or similar pan. The U.S. Weather Bureau class A pan is a cylindrical container fabricated of galvanized iron or monel metal with a depth of ten inches and a diameter of forty-eight inches. The pan is accurately leveled at a site which is nearly flat, well sodded, and free from obstructions. The pan is filled with water to a depth of eight inches, and periodic measurements are made of the changes of the water level with the aid of a hook gauge set in the stilling well. When the water level drops to seven inches, the pan is refilled (Hill, 1994).

Peak ET: The maximum ET rate during the growing season. This rate is commonly used to design irrigation systems (SCS, 1993).

Potential Evapotranspiration: The maximum rate at which water, if available, would be removed from the soil and plant surfaces. Expressed as the rate of latent heat transfer per square centimeter or depth of water (Hill, 1994).

Reference Crop Evapotranspiration: The evapotranspiration from a thick, healthy, well maintained grass (cool-season) that does not suffer any water stress. The reference crop ET_o is used to represent the water use of a standard crop in that environment even though that crop may not be physically grown in the area (SCS, 1993).

Relative Humidity: The dimensionless ratio of actual vapor pressure of the air to saturation vapor pressure, commonly expressed in percentage (Jensen et al., 1990).

Root Zone: the depth to which plant roots invade the soil and where water extraction occurs (Hill, 1994).

Saturation Deficit: (also called vapor pressure deficit) The difference between the actual vapor pressure and the saturation vapor pressure at the existing temperature (Hill, 1994).

Short-Wave Radiation: A term used loosely to distinguish solar and diffuse sky radiation from long-wave radiation (Jensen et al., 1990).

Soil-Water Balance: A procedure to record the additions and withdrawals of water from the crop root zone and to determine the amount of available water remaining in the root zone at a desired time (SCS, 1993)

Transpiration: The process by which water in plants is transferred as water vapor to the atmosphere (Jensen et al., 1990).

Unavailable Soil Moisture: Water in the root zone that is held so firmly by various forces that it usually cannot be absorbed by plants (Hill, 1994).

Wilting Point: The soil moisture content at which a plant can no longer obtain sufficient moisture to satisfy its requirements and, therefore, will wilt permanently (Hill, 1994).

Wind Run: Accumulated wind travel past a given point during a 24-hour period. For use in the Penman-Monteith equation, the wind run data are for 2 meters above the ground (Hill, 1994).

Vapor Pressure: The partial pressure of water vapor in the atmosphere (Jensen et al., 1990).

Symbols

α = albedo of crop and soil surface (fraction)
γ = psychrometric constant (mb/deg F)
$\gamma*$ = adjusted psychrometric constant = $\gamma(1+r_a/r_c)$ (mb/deg F)
γ_s = adjusted psychrometric constant (mb/deg F)
Δ = slope of vapor pressure curve (mb/deg F)
ε = net atmospheric emittance
λ = heat of vaporization of water (lang/in)
θ_d = solar declination angle (degrees)
Θ_{fc} = volumetric water content at field capacity (percent)
θ_m = solar altitude at solar noon (degrees)
Θ_{pwp} = volumetric water content at the permanent wilting point (percent)
ρ = density of air (lb/ft^3)
σ = Stephan Boltzman constant
a = empirical slope in longwave radiation equation
a1 = factor to account for the change of emissivity because of day length
A = the area irrigated by the lateral (acres)
A_u = the fraction of the field that is deficiently irrigated (percent)
AW = available soil water (in.)
b = empirical intercept for longwave radiation equation
B = cosine coefficient in clear sky radiation equation
BP = barometric pressure (mb)
cp = specific heat of dry air (lang/in/deg F)
d = displacement height of wind profile (m)
d = the gross depth of water per irrigation application (in.)
d_n = net depth of irrigation water applied during a normal irrigation (in.)
D = normal depth of irrigation prior to irrigation (in.)
D_t = total available soil water in the root zone (in.)
D_p = depleted available soil water from entire root zone (in.)
D_t = total available soil water in the root zone (in.)
DOY = the day of the year
e_z^o = average saturated vapor pressure at height z above the surface (mb)
e_z = actual vapor pressure at height z above the soil surface (mb)
ed = saturated vapor pressure at the dew point temperature (mb)
eo = saturation vapor pressure (mb)
eoz = average saturated vapor pressure for the day (mb)
eozmax = saturated vapor pressure at the maximum temperature (mb)
eozmin = saturated vapor pressure at the minimum temperature (mb)
E_c = conveyance efficiency (percent)
E_{soil} = the water loss due to evaporation during the non-cropped period (in./mon)
E_x = extraction efficiency (percent)

Elev = elevation above sea level (ft)
EA = water application efficiency (decimal)
EC_w = electrical conductivity of the irrigation water (mmhos/cm)
EC_e = estimated electrical conductivity of the average saturation extract of the soil root zone profile for an approximate yield reduction (mmhos/cm)
ES = the water storage efficiency (percent)
ET = crop evapotranspiration during a period (in.)
ET_{crop} = crop water use or evapotranspiration (in./d)
ET_o = the evapotranspiration rate for a grass reference crop (in./d)
ET_{peak} = the peak use rate of the crop (in./d)
ET_r = reference ET for 20 inch tall alfalfa (in./d)
Evap = evaporation of water (cm/day)
f(D) = function to account for depth of soil moisture depletion other than 3 inches
f_p = interval between significant rains or irrigations (days)
F_{S1} = fraction of growing season at end of initial crop growth stage
F_{S2} = fraction of growing season at end of canopy development stage
F_{S3} = fraction of growing season at end of mid-season growth stage
F_w = the relative portion of the soil surface originally wetted (fraction)
G = soil heat flux (lang/d)
hc^* = crop height (in.)
I_{net} = seasonal net irrigation (in.)
IE = the irrigation efficiency (percent)
K_1 = unit conversion constant for Penman-Monteith equation
K_c = crop coefficient
K_{cb} = basal crop coefficient
$\overline{K}_{cb}$ = the weighted value of the basal crop coefficient K_{cb} for the wetland
K_{cm} = value of basal crop coefficient at crop maturity
K_{cp} = peak or maximum value of basal crop coefficient
K_o = von Karman's constant ≅ 0.40 (dimensionless)
K_s = the factor related to water stress
K_w = factor to account for the increased evaporation from wet soils following a rain or irrigation
L = the effective length of the wetland parallel to the predominant wind direction (ft)
Lat = latitude (degrees)
Le_t = turbulent Lewis number, $Le_t = 1$ (dimensionless)
LR = leaching requirement ratio for sprinkle or surface irrigation (decimal)
n = the number of locations where measurements were made
nN = ratio of actual (n) to maximum possible sunshine hours (N)
P = cumulative probability (percent)
P_{ef} = effective precipitation (in./mon)
P_t = total precipitation (in./mon)
Pr_t = turbulent Prandtl number ≅ 0.885 (dimensionless)

Q = water needed by the center pivot or hydraulic design capacity (gpm)
Q_a = incoming long-wave atmospheric radiation (cal/cm^2/day)
Q_{ar} = reflected atmospheric radiation (cal/cm^2/day)
Q_{bs} = long-wave radiation emitted by the body of water (cal/cm^2/day)
Q_e = energy used by evaporation (cal/cm^2/day)
Q_h = energy conducted by the body of water as sensible heat (cal/cm^2/day)
Q_n = net solar radiation (cal/(cm^2-sec))
Q_o = change in energy stored in the body of water (cal/cm^2/day)
Q_r = reflected solar radiation (cal/cm^2/day)
Q_s = short-wave solar radiation incident to the water surface (cal/cm^2/day)
Q_v = net energy advected into the lake by inflow and withdrawal (cal/cm^2/day)
Q_w = energy advected in the evaporated water (cal/cm^2/day)
r_a = aerodynamic resistance to sensible heat and vapor transfer (d/mi)
r_c = surface resistance to vapor transport (d/mi)
R_d = root zone depth (in.)
R_e = the effective precipitation during the growing season (in.)
R_n = net radiation (lang/d)
Rb = net outgoing longwave radiation (lang/d)
Rbo = the net outgoing longwave solar radiation on a clear day (lang/d)
Reso = clear sky radiation correction term for elevation (lang/d)
Rh_{min} = mean monthly minimum relative humidity (percent)
Roso = clear sky radiation at sea level (lang/d)
Rs = incoming solar radiation (lang/d)
Rso = the amount of incident solar radiation on a clear day (lang/d)
S = velocity ratio of $U / \overline{U}$ (dimensionless)
t = elapsed time since wetting (days)
t_{bi} = the time between irrigation events (days)
t_d = time required for the soil surface to dry (days)
t_l = the lateral operating time for one irrigation (day
T = ambient temperature in degrees absolute (°K)
Ta = mean air temperature (deg F)
Tmax = maximum air temperature for the day (deg F)
Tmin = minimum air temperature for the day (deg F)
Ts4 = effective absolute temperature of the earth's surface raised to the fourth power (deg K)
U = wind velocity (m/s)
$\overline{U}$ = average wind velocity for the period (m/s)
U_z = adjusted average daytime wind velocity (m/s)
Uf = adjustment factor for wind speed that correct for vegetation at weather station (dimensionless)
Uz = wind run at height Zw (miles/day)
UCC = Christiansen's uniformity coefficient (Cuenca, 1989) (percent)
V_a = the volume of water applied to the field (ac-ft)
V_b = the volume of water beneficially used (ac-ft)

$V_{app\text{-}dev}$ = volume of water delivered to application devices (sprinkler, furrow system, etc.) (ac-ft)
$V_{distsys}$ = volume delivered to distribution system (canal or pipeline) (ac-ft)
$V_{extract}$ = volume extracted from supply (well, reservoir, or stream) (ac-ft)
V_{nrs} = the volume or average depth of water needed in the root zone to bring the root zone up to field capacity (ac-ft)
V_{root_zone} = volume of water stored in the root zone (ac-ft)
V_{srs} = the volume or average depth of water stored in the root zone during the irrigation (ac-ft)
W = the width of the wetland perpendicular to the predominant wind direction (ft)
W_{et} = the total seasonal evapotranspiration (in.)
W_l = the leaching requirement (in.)
W_s = the water stored in the soil during the off-season (in.)
WF = Wetting factor (fraction)
x_i = the catch or depth of water at individual locations (in.)
$\bar{x}$ = the average catch or depth of water of all locations (in.)
z = reference height of wind measurement above ground (m)
z_o = aerodynamic roughness (m)
Zp = height of air temperature measurement (ft)
Zw = height of wind speed measurement (ft)

Appendix B

Climatic Data

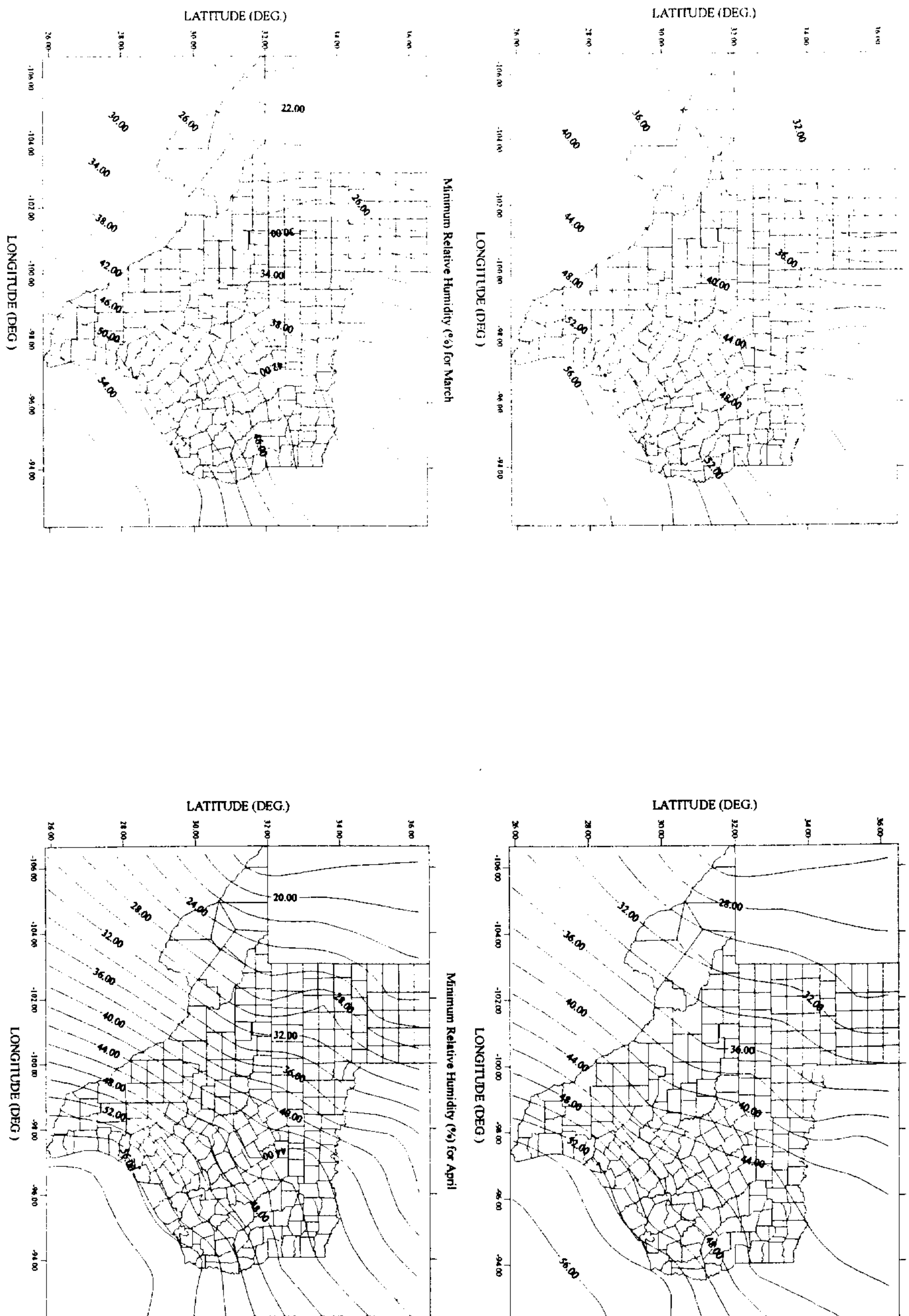


Figure B1.-Minimum Relative Humidity.

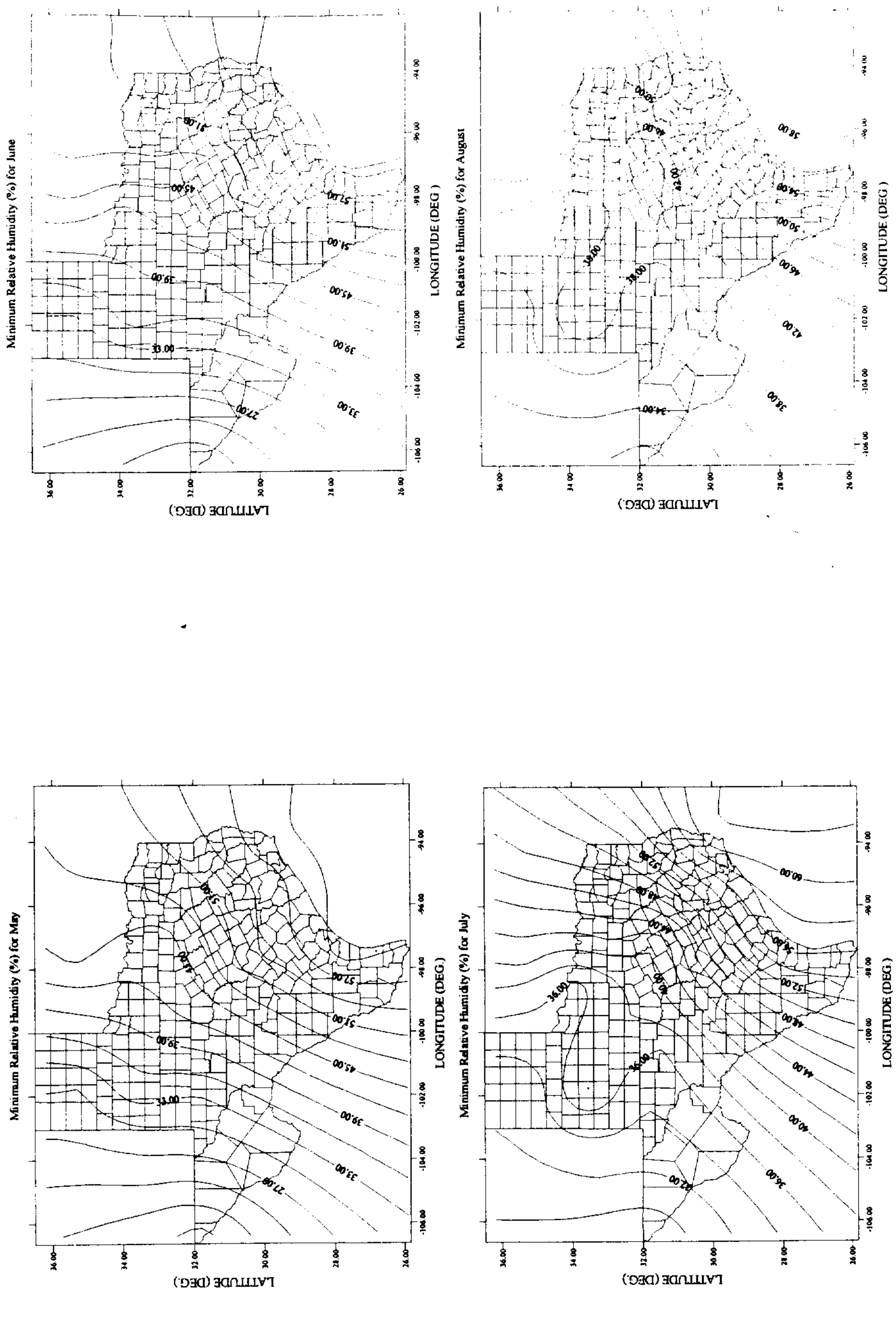


Figure B1.-Minimum Relative Humidity.

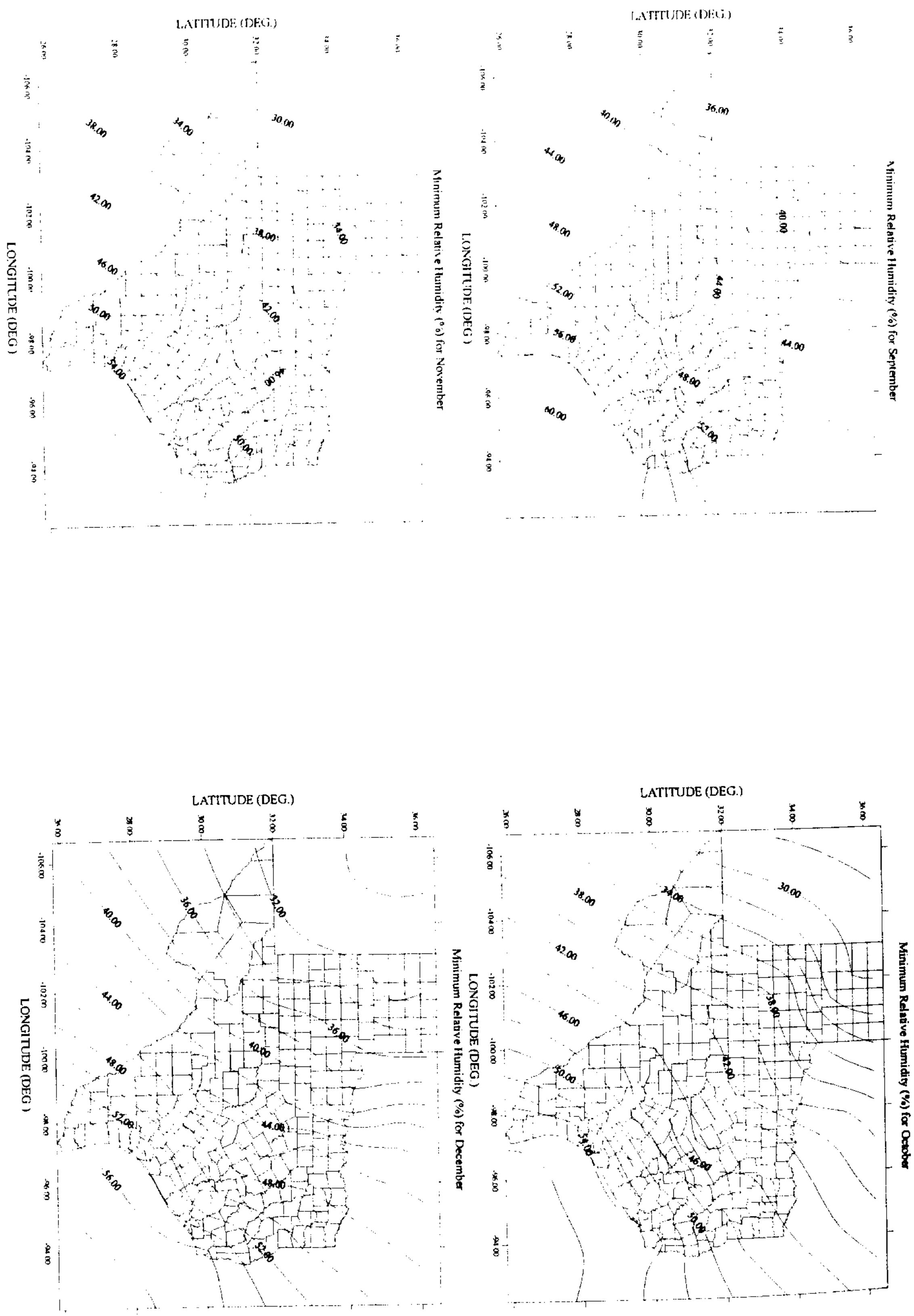


Figure B1.-Minimum Relative Humidity.

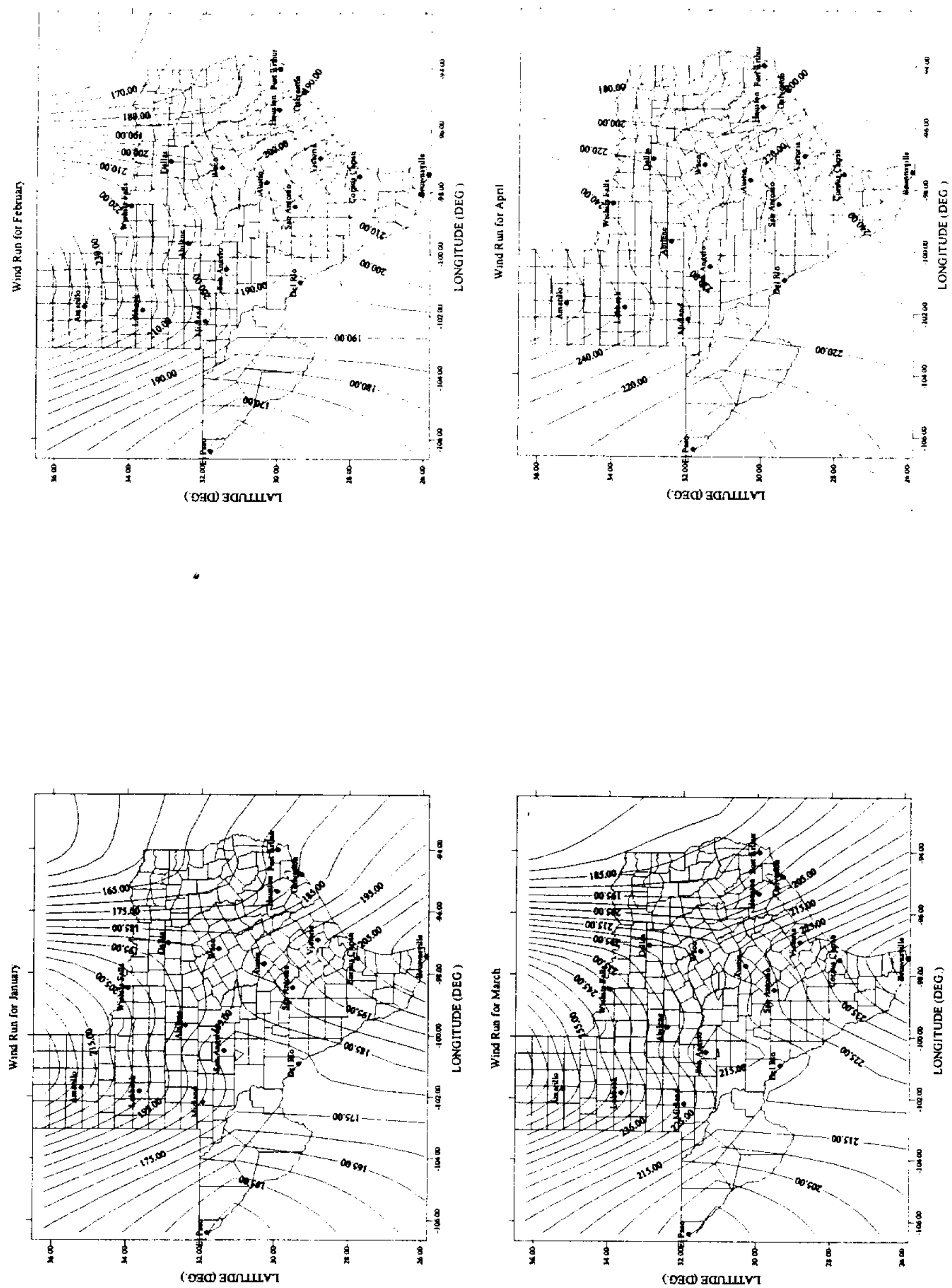


Figure B2.-Wind Run (miles per day) Adjusted to 2 m Height.

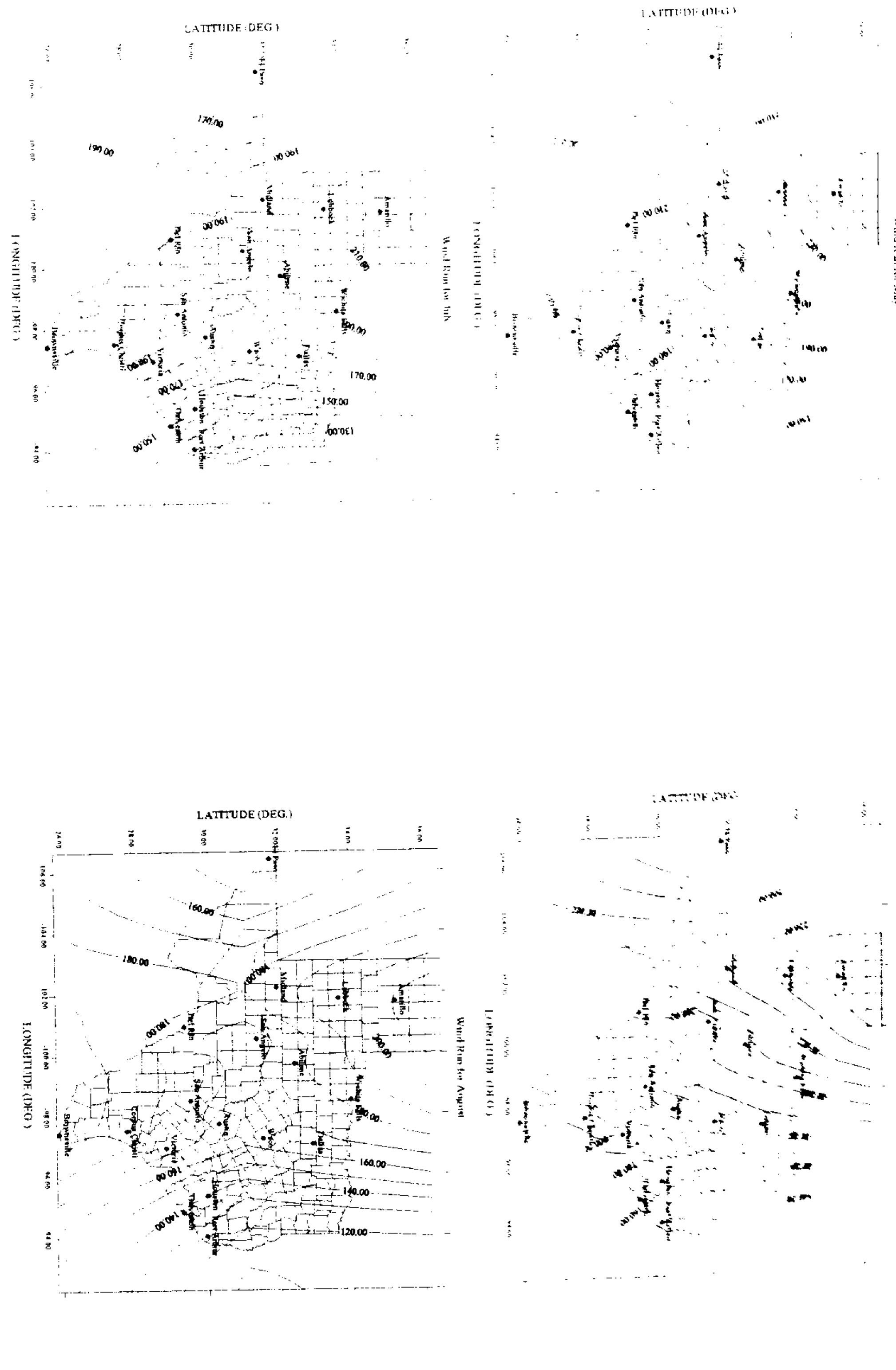


Figure B2.-Wind Run (miles per day) Adjusted to 2 m Height.

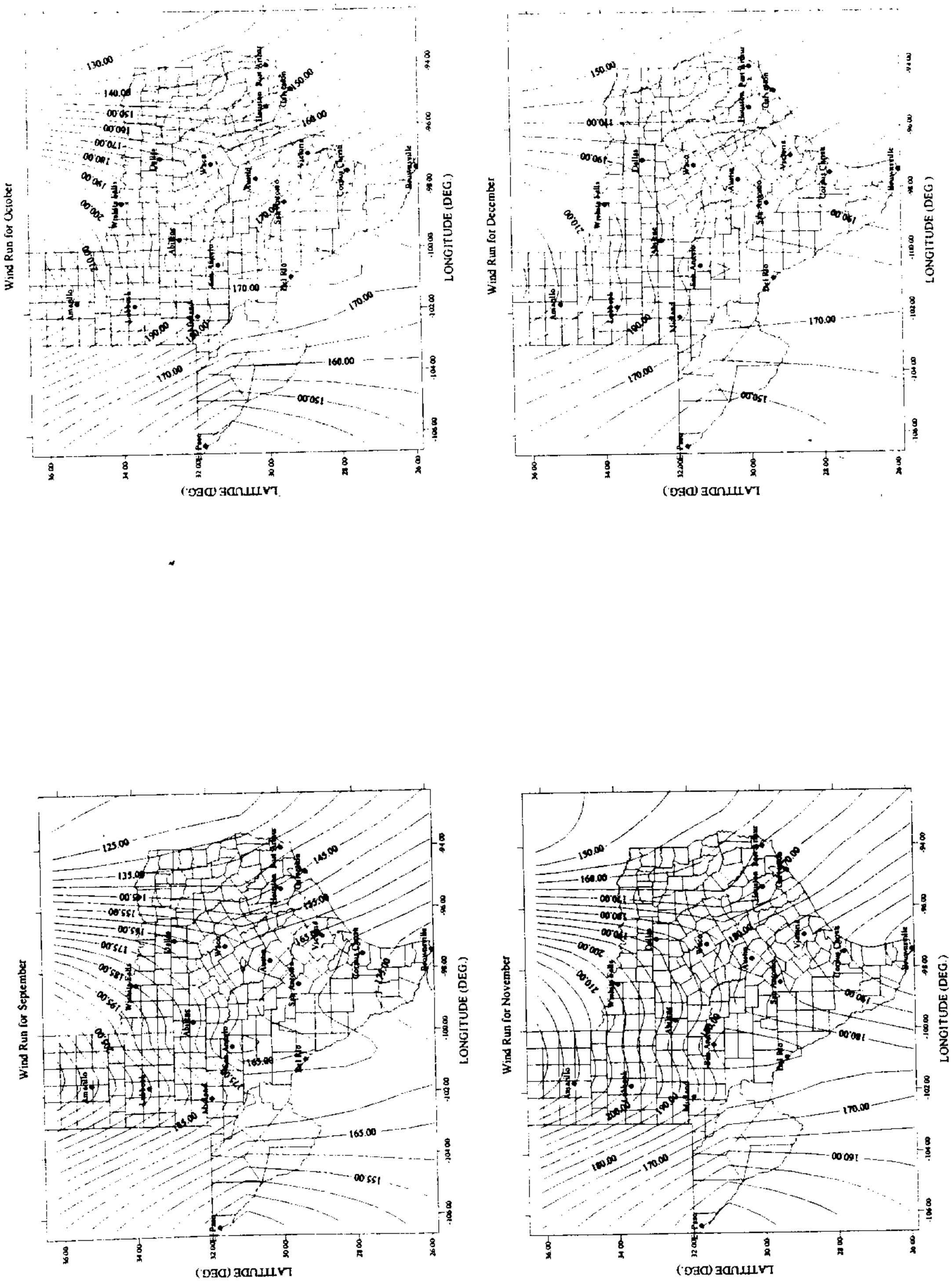


Figure B2.-Wind Run (miles per day) Adjusted to 2 m Height.

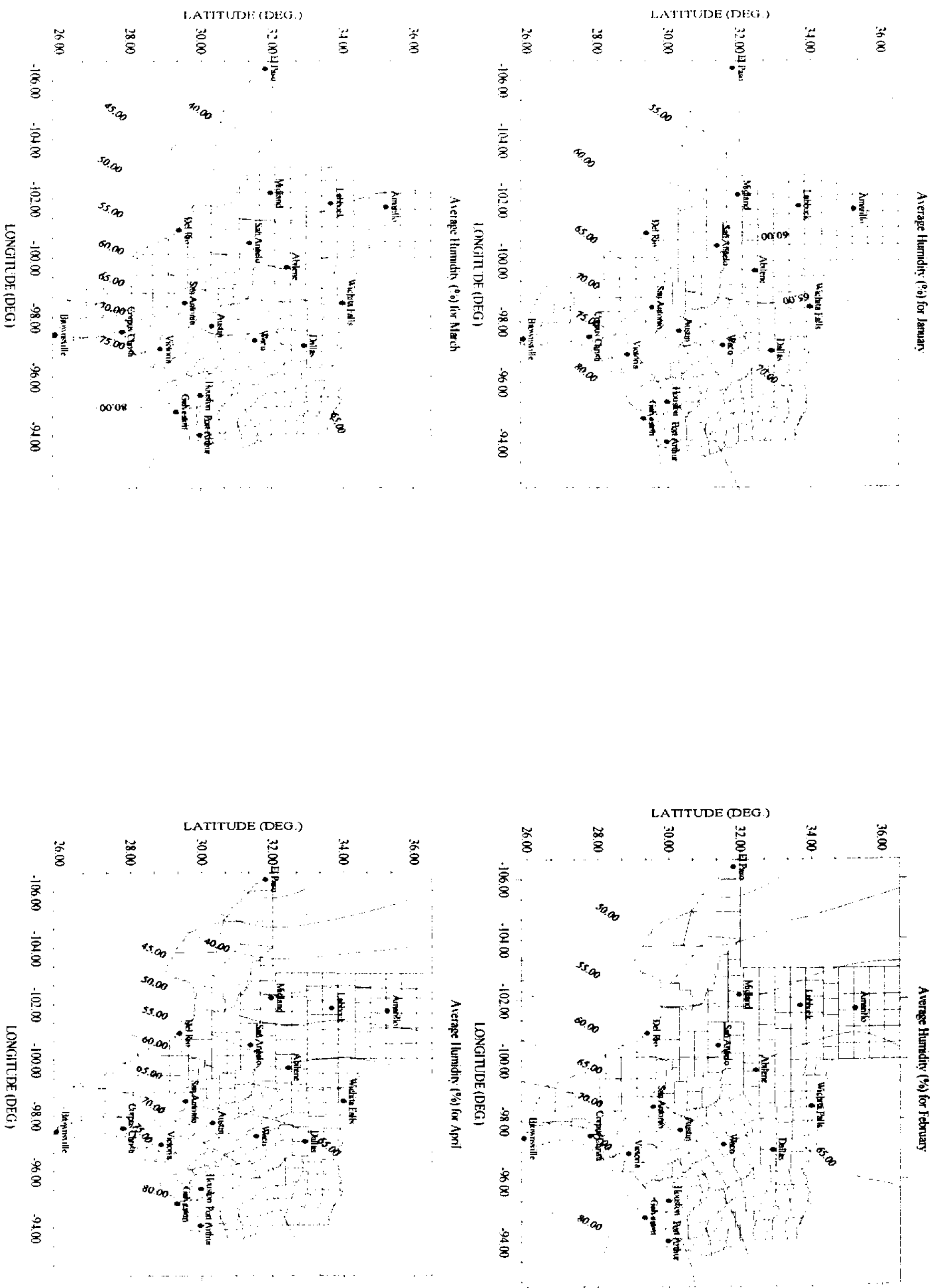


Figure B3.-Mean Monthly Average Humidity (percent).

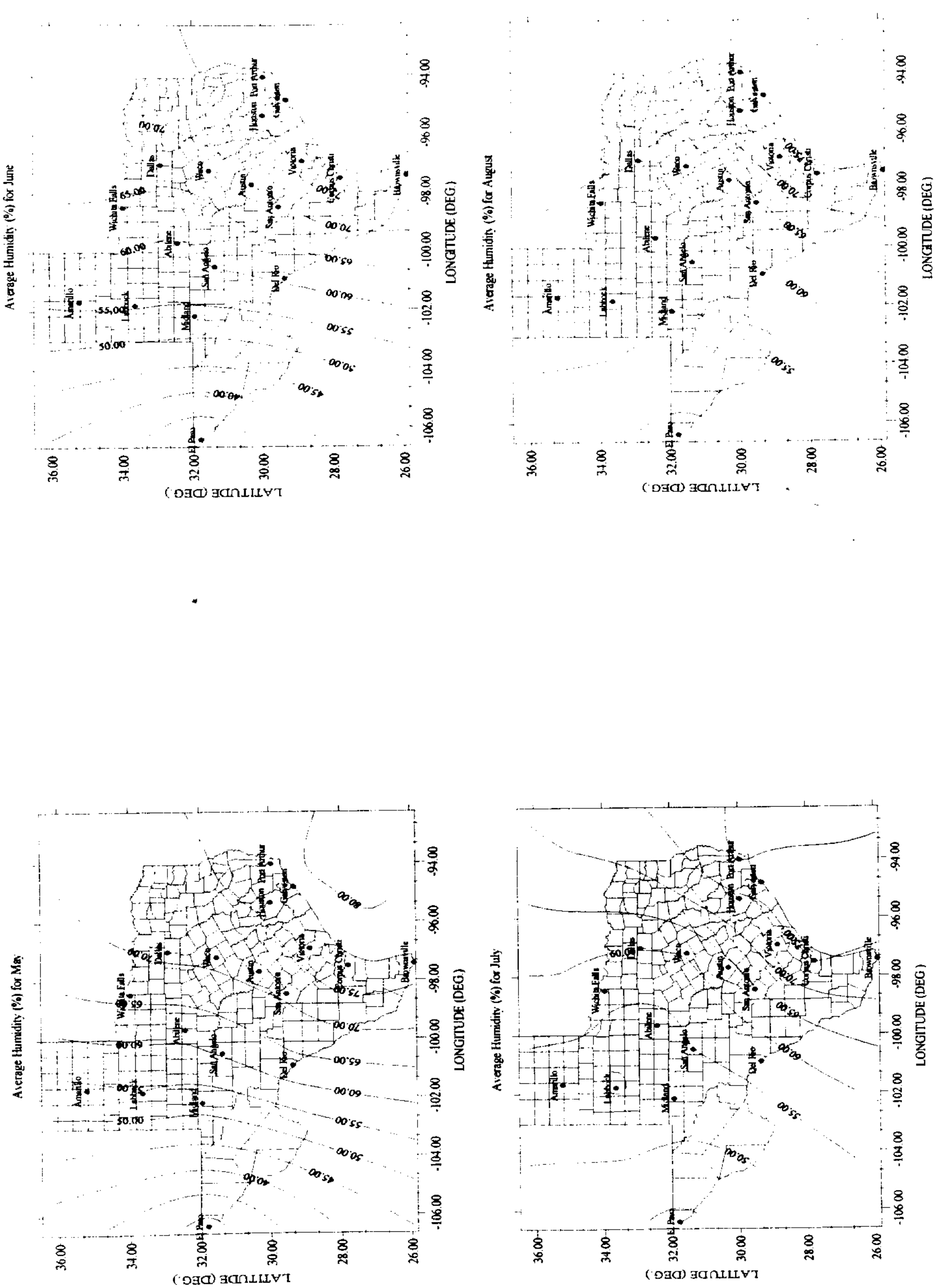


Figure B3.-Mean Monthly Average Humidity (percent).

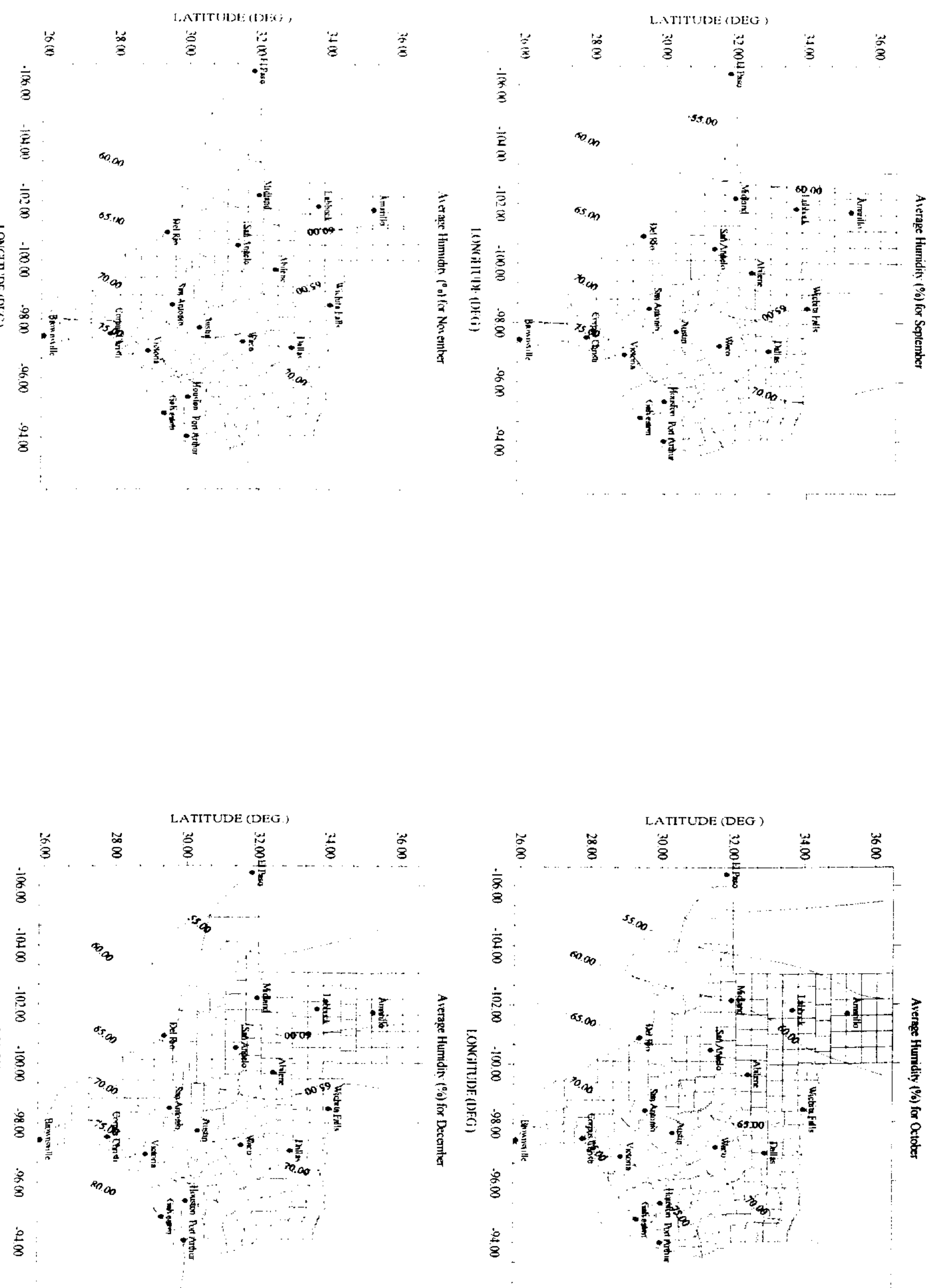


Figure B3.-Mean Monthly Average Humidity (percent).

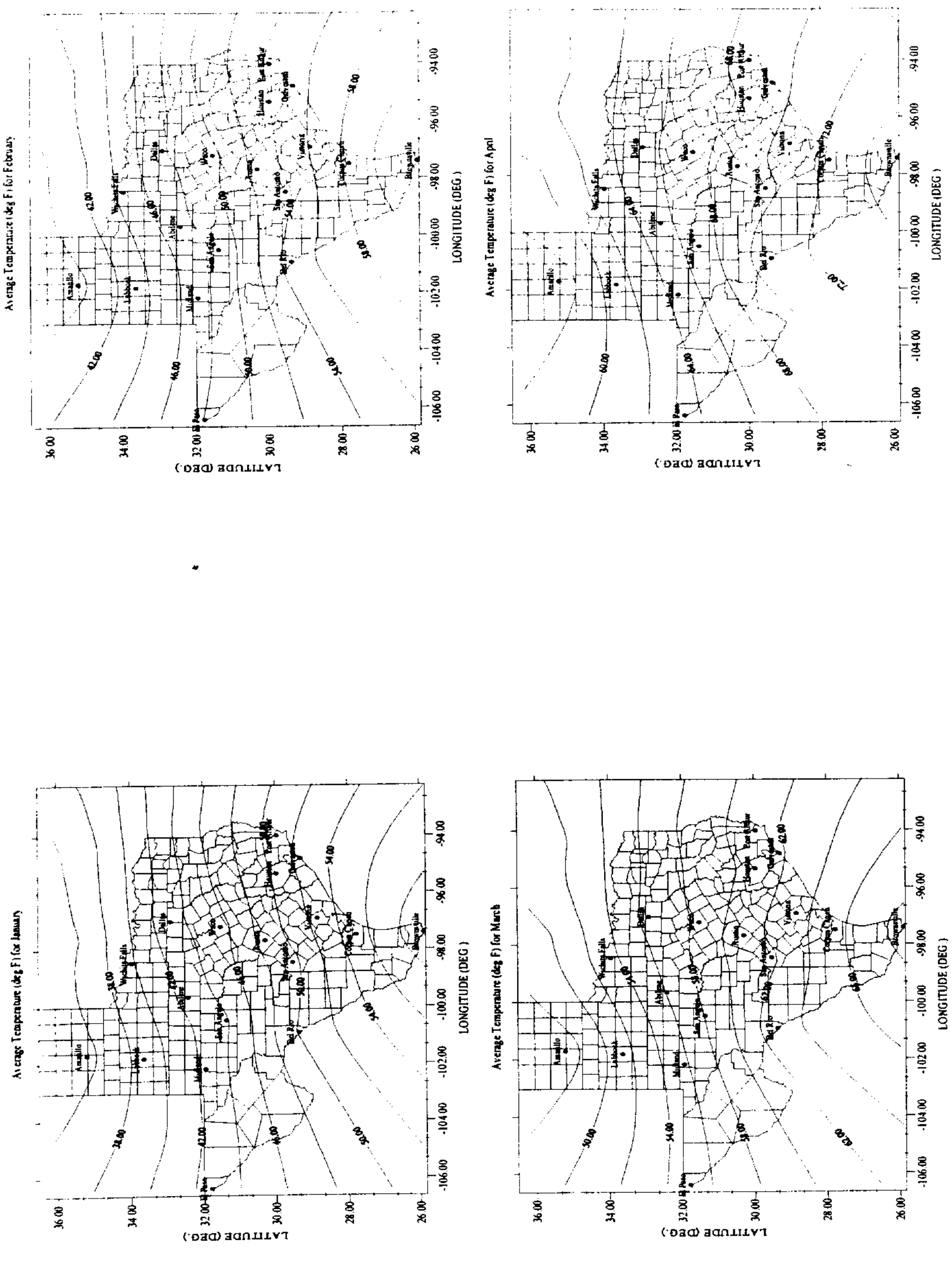


Figure B4.-Mean Monthly Average Temperatures (deg F).

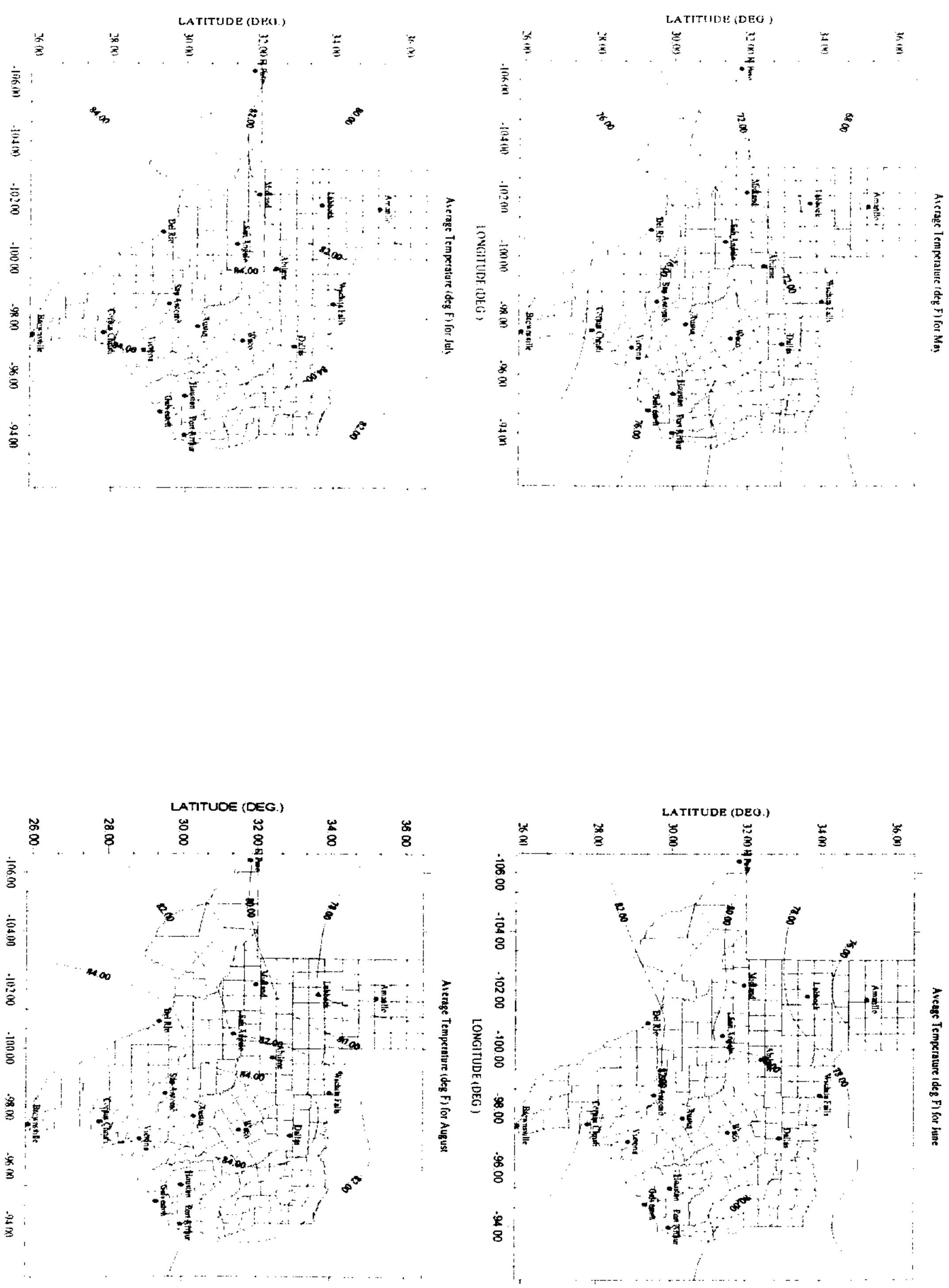


Figure B4.-Mean Monthly Average Temperatures (deg F).

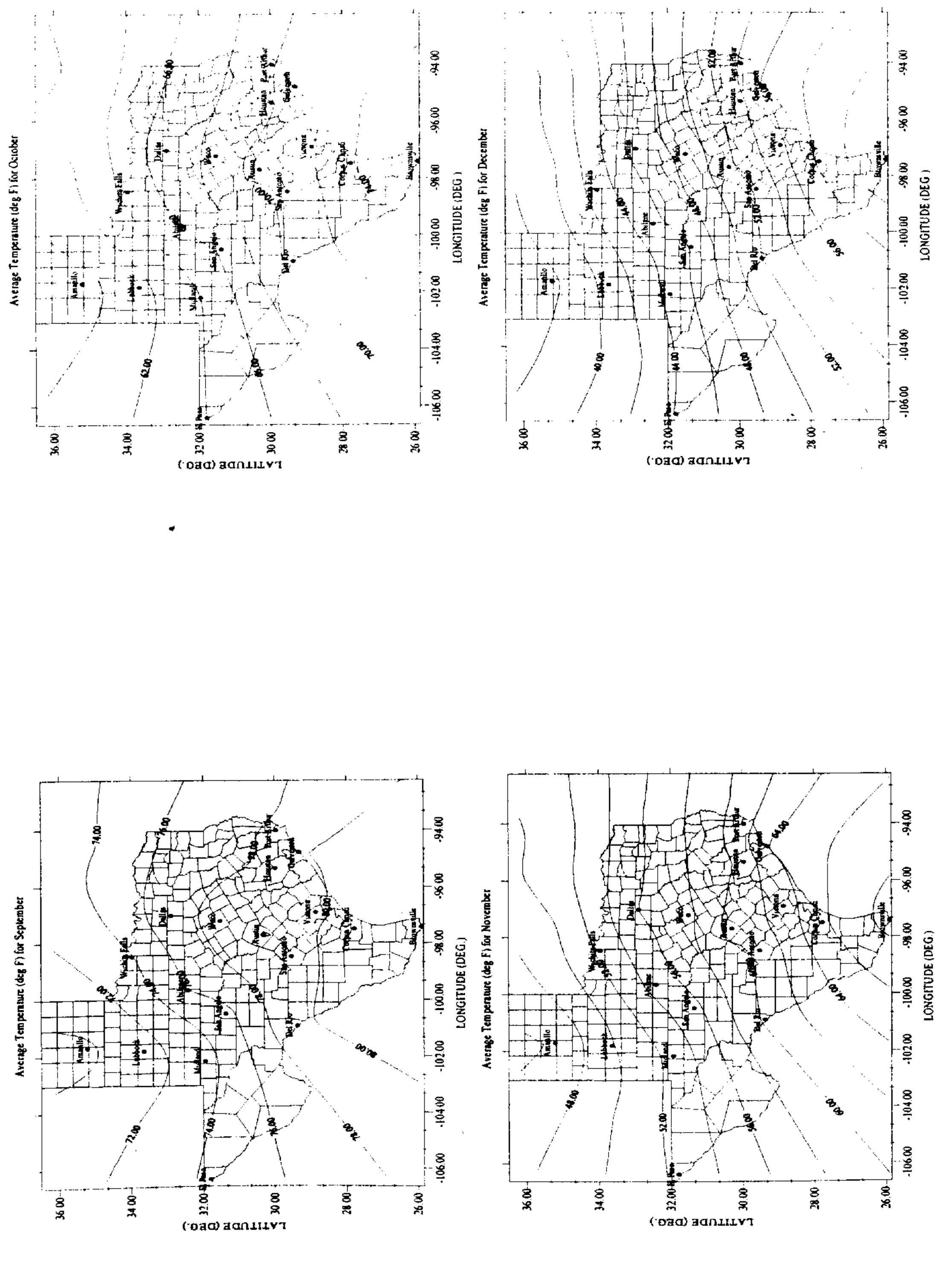


Figure B4.-Mean Monthly Average Temperatures (deg F).

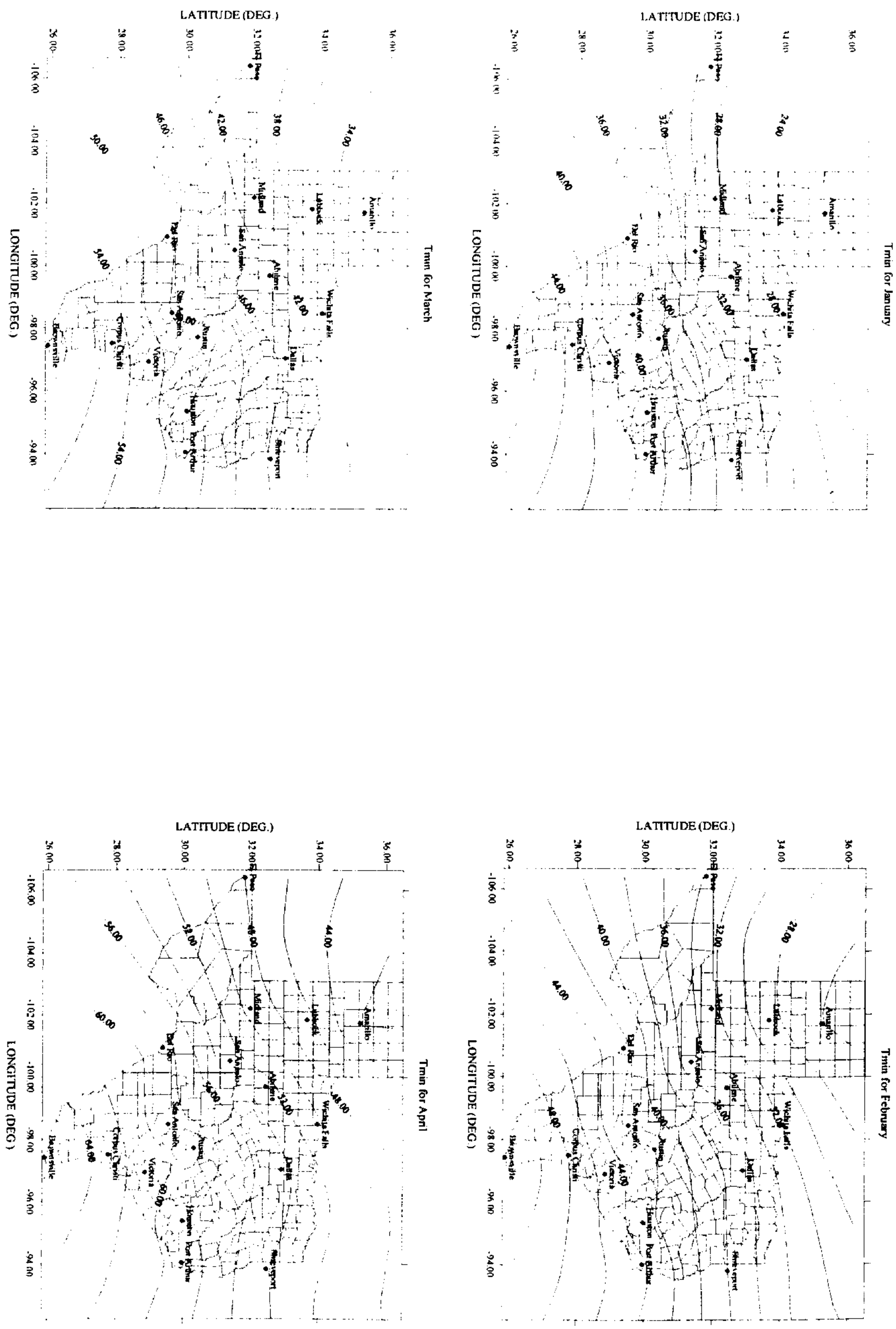


Figure B5.-Mean Monthly Minimum Temperatures (deg F).

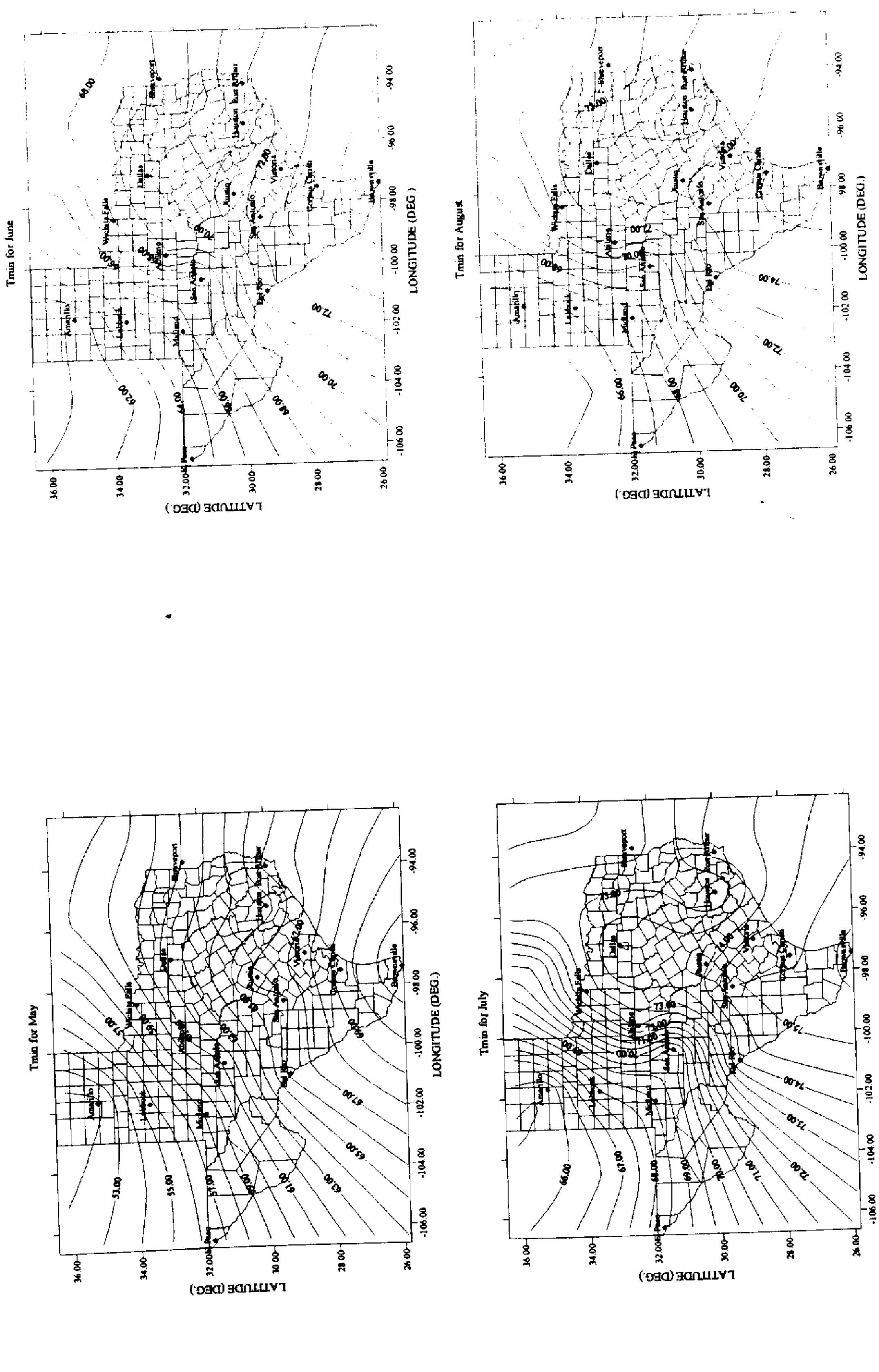


Figure B5.-Mean Monthly Minimum Temperatures (deg F).

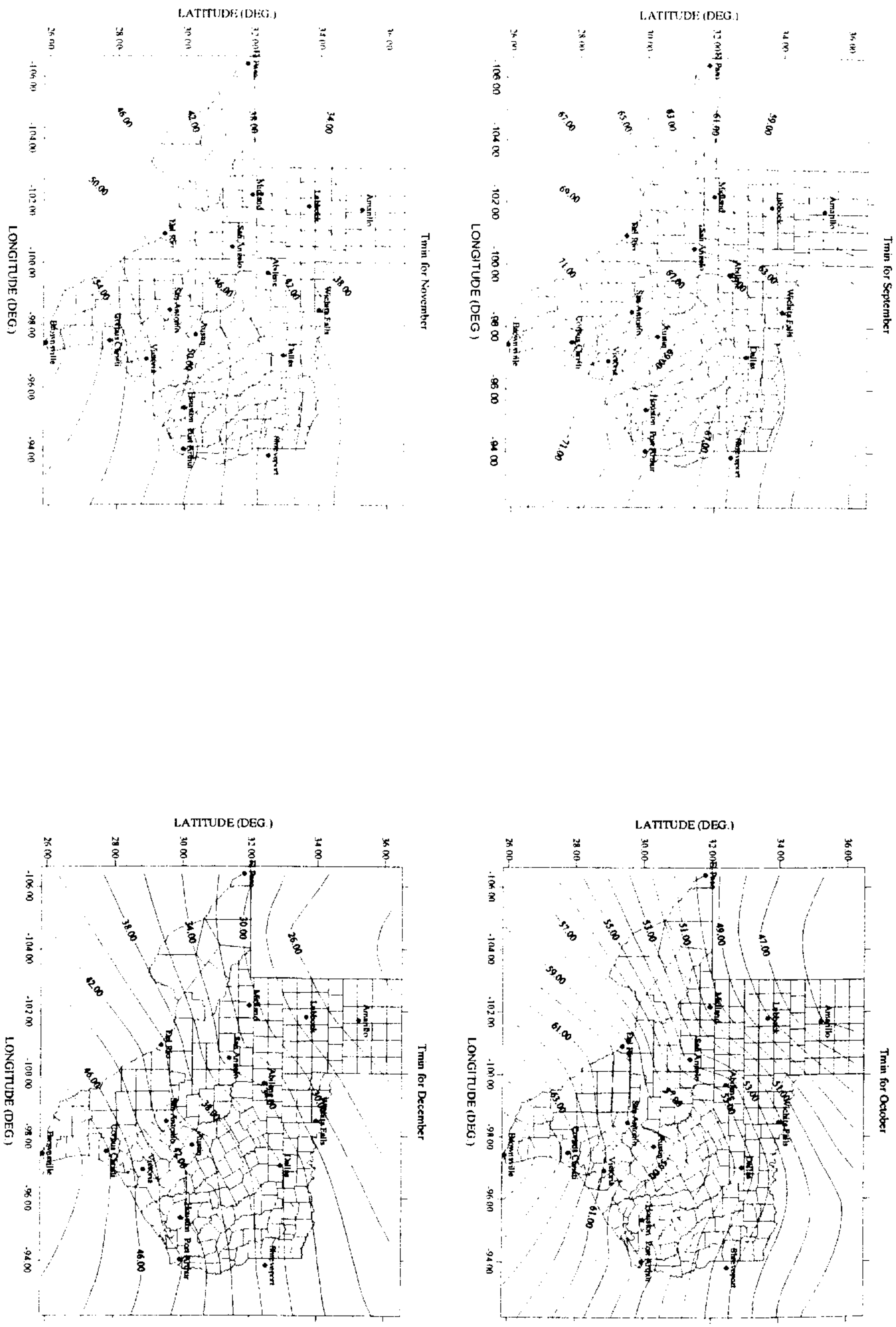


Figure B5-Mean Monthly Minimum Temperatures (deg F).

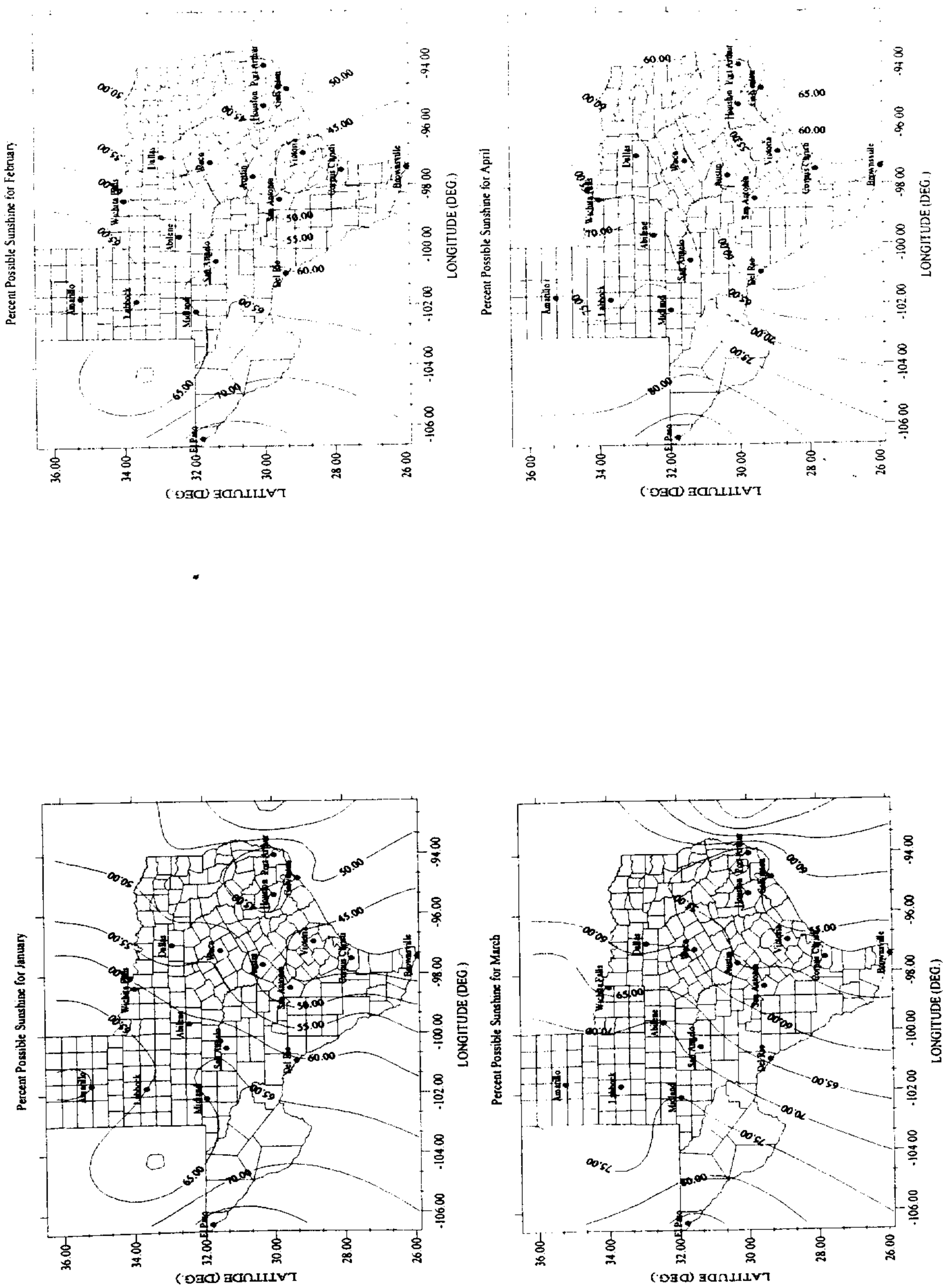


Figure B6.-Percent Possible Sunshine.

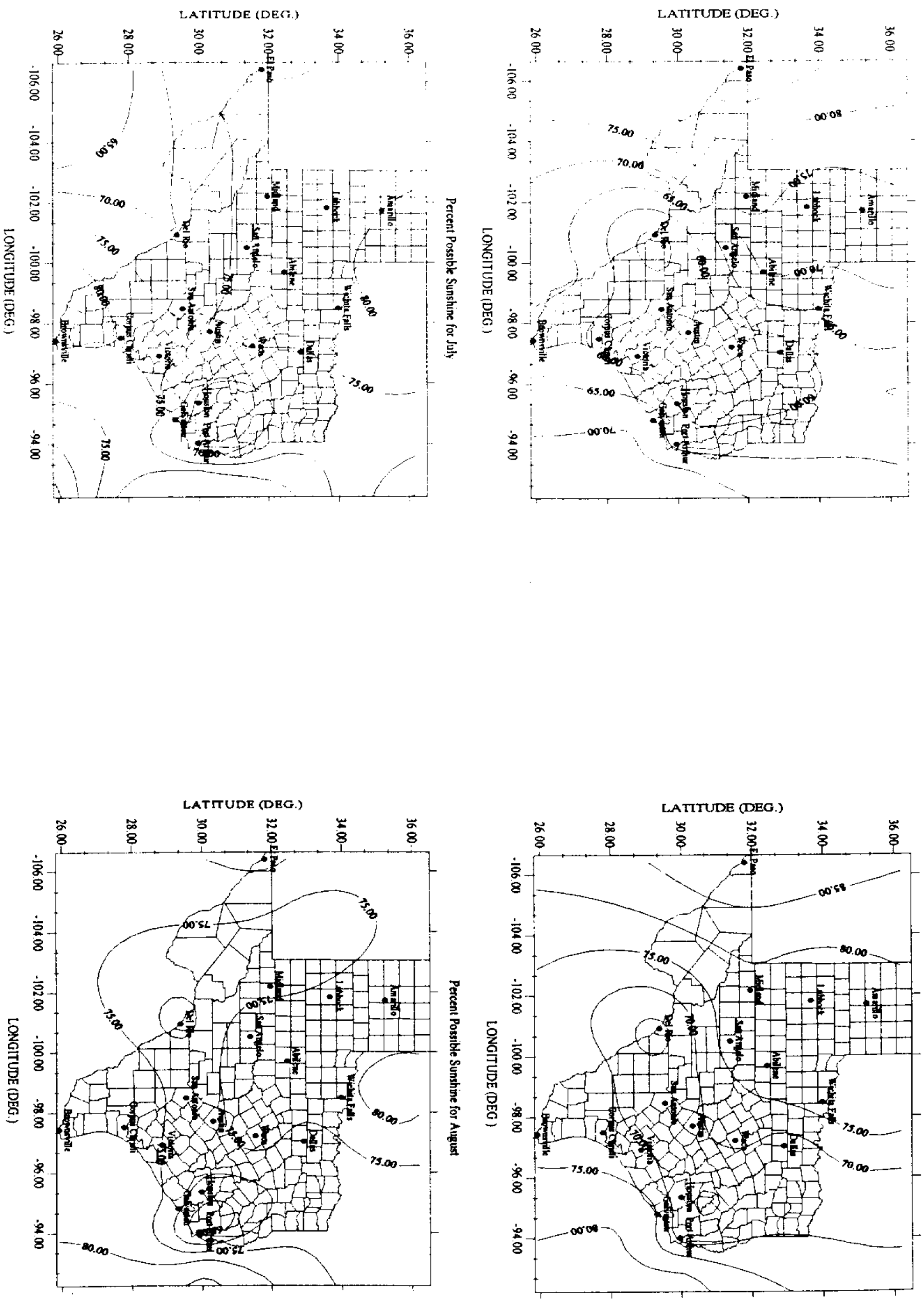


Figure B6.--Percent Possible Sunshine.

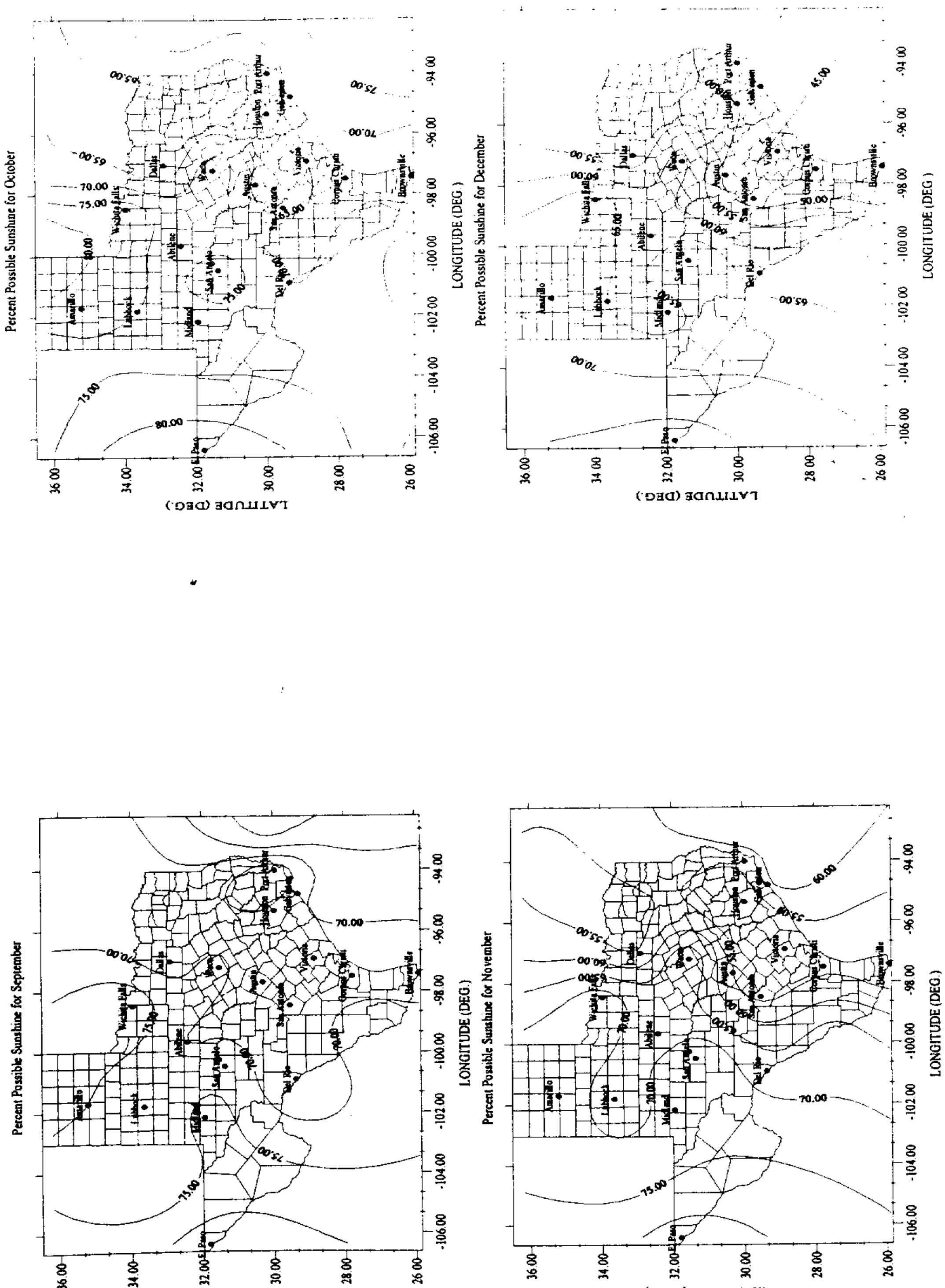


Figure B6.--Percent Possible Sunshine.

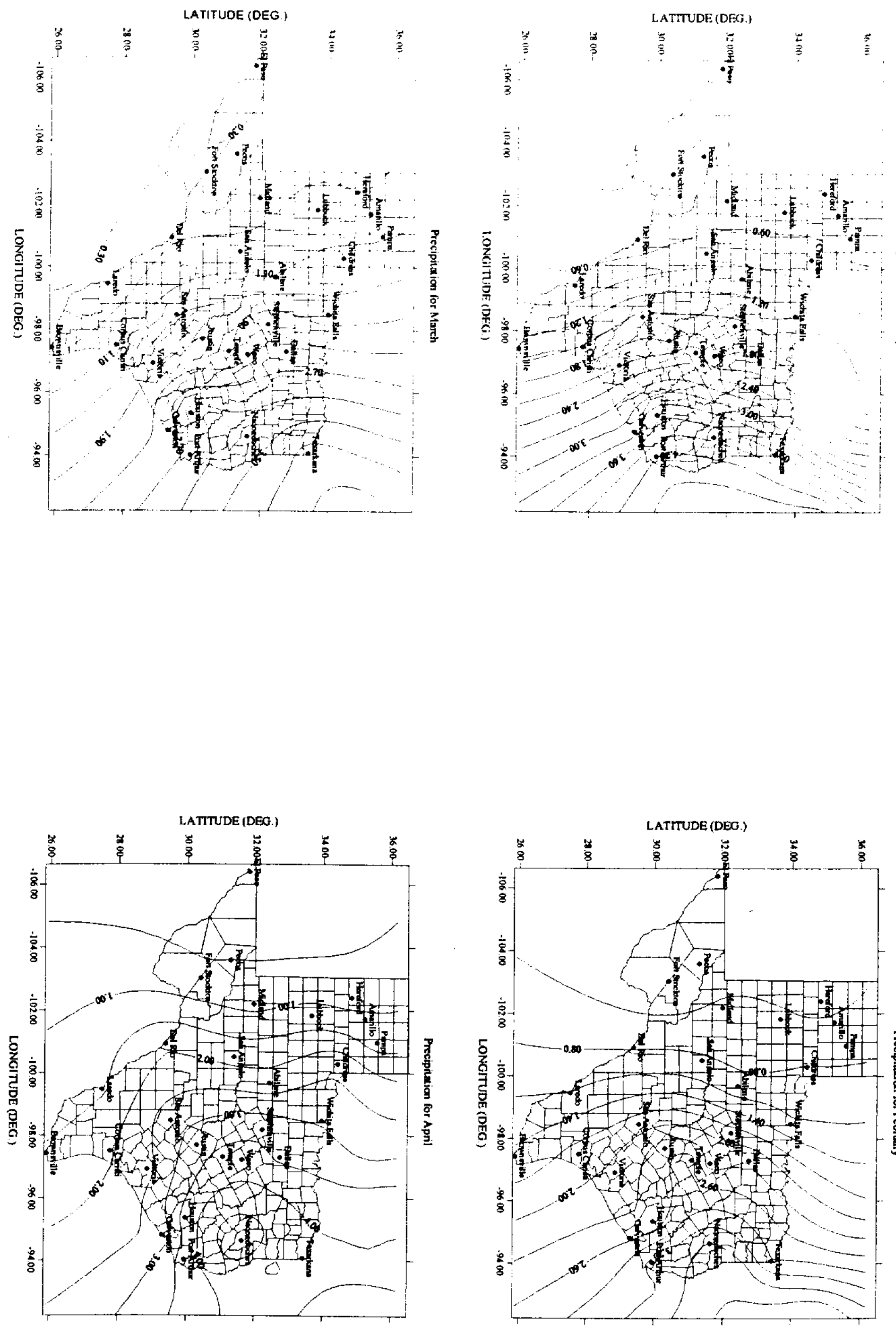


Figure B7.-Mean Monthly Precipitation (inches per month).

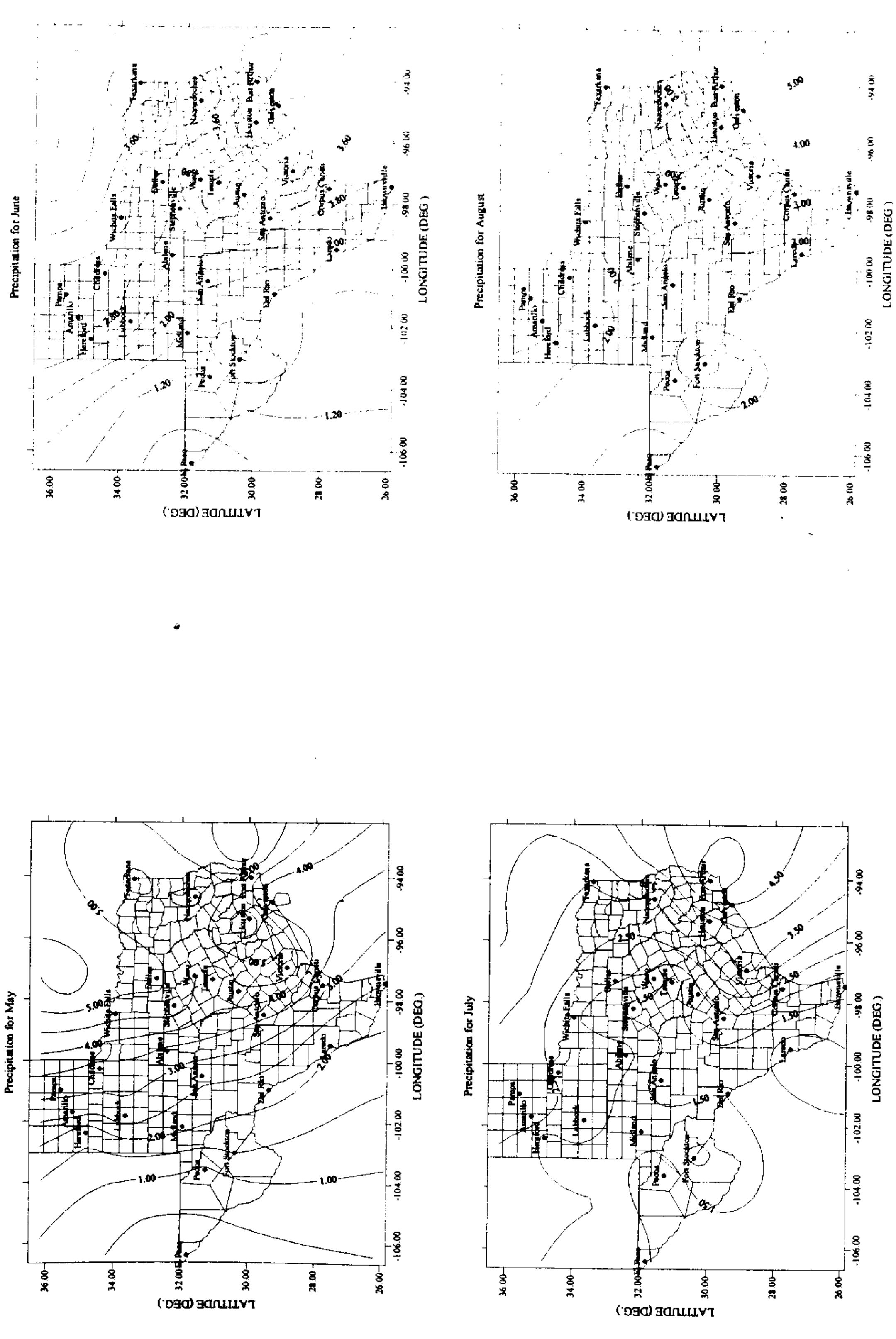


Figure B7.-Mean Monthly Precipitation (inches per month).

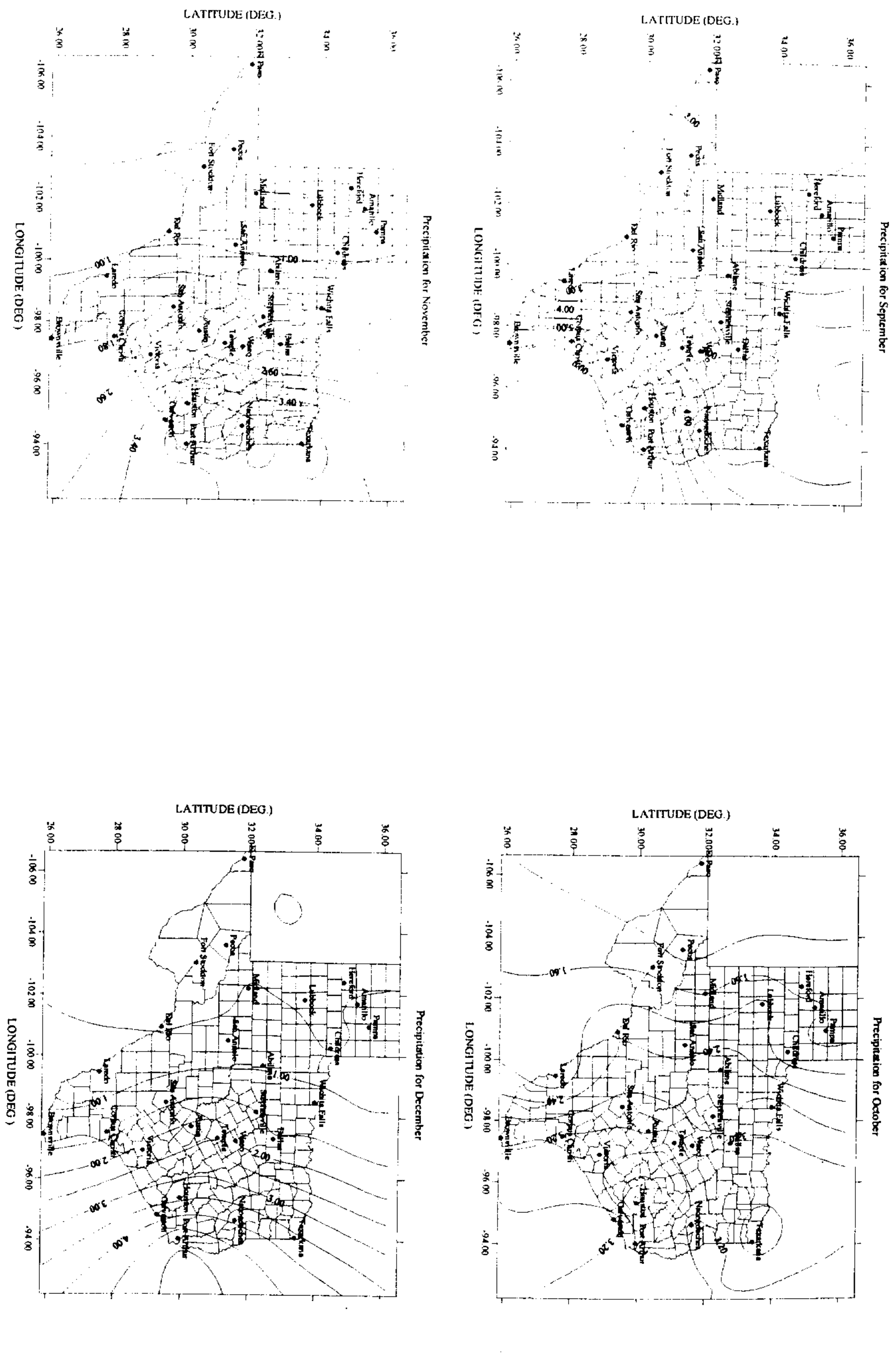


Figure B7.-Mean Monthly Precipitation (inches per month).

Table B1.-Minimum Relative Humidity.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	38.91	38.22	35.06	36.80	41.52	41.27	37.97	39.22	43.77	41.37	41.33	39.82
Alice	52.60	50.40	50.00	54.00	58.30	57.00	53.75	53.50	55.50	52.60	52.00	52.00
Amarillo	29.92	30.25	25.03	24.42	30.10	32.94	32.64	35.29	35.30	30.29	29.58	31.66
Austin	46.97	45.13	44.66	48.28	53.49	51.22	46.73	45.75	48.93	46.54	47.33	46.73
Beaumont	55.30	52.40	52.80	56.00	58.20	59.50	59.60	59.40	59.30	54.00	54.30	55.30
Brownfield	33.90	32.30	27.70	27.90	32.75	35.00	36.05	37.53	40.30	36.60	34.80	34.00
Brownsville	57.39	54.93	54.36	57.18	59.71	58.94	56.06	55.55	57.78	55.56	55.78	56.70
Brownwood	41.25	40.00	37.10	39.60	44.40	43.30	39.20	39.20	44.40	42.60	42.60	41.75
Childress	34.60	34.25	30.20	31.00	37.00	38.00	35.42	35.43	39.30	36.00	35.10	35.70
College Station	49.00	47.00	46.30	48.90	52.60	52.00	48.60	47.90	50.50	47.50	48.15	48.50
Corpus Christi	54.82	52.63	52.51	56.78	61.13	59.48	56.10	56.10	57.55	54.73	53.94	53.54
Crockett	49.60	47.00	46.40	49.00	51.80	52.50	50.00	49.30	51.40	48.15	48.90	49.60
Dalhart	30.90	29.50	23.90	23.00	28.50	31.15	32.40	35.00	35.00	29.50	29.00	31.60
Dallas	45.51	44.09	43.30	45.75	43.71	47.34	42.26	42.80	47.86	45.79	46.74	46.67
Dumas	30.80	30.00	24.85	24.00	29.75	32.40	33.00	35.40	35.42	30.00	29.60	31.80
El Paso	31.05	24.55	19.61	16.07	16.96	18.04	28.49	31.33	33.06	28.24	27.89	31.62
Falfurrias	53.50	51.40	50.70	54.40	58.40	57.20	54.00	53.90	56.00	53.40	52.70	53.00
Fort Davis	33.00	31.00	26.00	25.00	28.50	30.00	33.60	35.65	39.40	35.90	34.45	34.90
Fort Hancock	32.30	26.50	21.60	18.90	20.50	21.70	30.20	32.80	35.00	30.60	29.80	32.70
Fort Stockton	33.30	32.60	27.25	27.30	31.50	33.10	34.50	36.40	41.00	37.85	35.85	35.50
Friona	31.50	30.10	25.10	24.50	29.40	31.80	33.90	36.60	36.85	31.85	30.80	31.80
Galveston	66.09	65.35	68.01	71.14	69.23	67.01	66.88	65.59	64.84	62.43	65.38	66.56
Graham	40.00	39.00	36.00	38.40	42.35	42.20	37.25	37.60	42.50	40.80	40.70	40.50
Guthrie	35.80	35.20	31.40	32.50	38.00	38.75	36.40	38.00	41.00	38.00	37.20	36.60
Hereford	31.60	30.30	25.30	24.70	29.75	32.40	33.85	36.50	36.60	31.70	30.65	31.80
Houston	51.06	48.61	50.04	52.01	54.60	55.72	54.47	54.27	55.42	50.96	51.27	50.94
Kerrville	42.90	40.80	39.10	42.60	48.00	47.00	43.40	42.80	47.00	44.60	43.75	43.60
Laredo	48.80	46.00	44.75	48.00	52.40	51.40	49.00	48.90	52.00	49.40	48.35	48.60
Llano	43.30	41.50	39.50	42.70	48.00	46.40	42.00	41.60	46.00	44.00	43.80	43.60
Lubbock	34.53	33.25	29.44	29.98	34.91	37.09	38.31	40.48	41.29	37.37	35.74	34.87

Table B1.-Minimum Relative Humidity (continued).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Marshall	49.35	45.80	44.65	47.40	51.30	52.70	50.60	49.80	51.30	47.50	48.70	49.83
McAllen	54.75	52.30	51.60	54.60	57.60	56.70	54.00	53.80	56.10	53.85	53.60	54.15
Midland	33.83	32.86	26.70	26.94	32.27	34.80	34.07	36.06	41.03	38.16	35.70	34.21
Morton	32.80	31.00	26.20	26.00	30.60	32.80	35.30	37.75	38.60	34.30	33.00	32.65
Nacogdoches	50.50	47.50	47.00	49.50	52.70	53.80	52.00	51.40	52.80	49.00	49.85	50.80
Pampa	32.00	32.00	27.00	26.90	33.00	35.40	33.85	35.95	36.50	32.00	31.50	33.50
Paris	46.50	44.10	42.20	44.50	46.60	49.60	45.90	45.40	46.50	45.10	46.30	47.50
Pecos	34.00	31.00	25.40	24.80	28.60	30.40	33.25	35.50	39.30	35.70	33.80	33.90
Perryton	32.50	31.20	27.00	26.90	33.35	35.60	33.95	35.80	36.40	31.85	31.30	33.80
Plainview	33.00	32.25	28.10	28.25	33.35	35.70	36.05	37.02	39.10	35.00	33.80	33.80
Port Arthur	56.16	53.36	53.59	56.90	59.05	60.53	60.69	60.68	60.41	54.93	55.70	56.17
Presidio	36.00	31.80	27.30	26.30	29.25	30.00	34.40	36.30	40.00	36.40	35.20	36.40
Roswell	32.59	28.35	22.88	21.60	24.98	26.04	32.18	35.04	36.08	31.06	29.94	30.52
San Angelo	38.10	35.97	32.02	33.55	39.67	39.38	35.97	37.35	44.85	42.48	40.71	39.65
San Antonio	44.72	42.70	41.96	46.40	51.58	50.86	47.49	46.18	48.60	45.71	45.00	45.32
Seymour	37.70	37.00	33.50	35.25	40.40	40.50	36.10	37.00	41.30	39.00	38.50	38.25
Sherman	44.90	43.00	41.30	43.80	45.20	47.80	42.70	42.70	44.70	44.25	45.00	46.00
Snyder	36.00	35.00	30.80	31.80	37.12	38.20	36.40	39.85	42.40	39.50	38.10	36.80
Sonora	39.00	36.80	33.30	35.00	40.90	40.50	37.85	38.80	45.00	42.60	40.90	40.25
Stephenville	42.40	41.40	38.60	41.20	44.60	43.80	39.00	39.00	43.50	42.67	42.70	42.80
Temple	46.40	44.65	42.20	45.30	50.20	47.70	42.60	41.40	45.40	44.00	44.70	45.60
Texarkana	48.30	45.20	43.30	45.85	50.35	51.80	50.00	49.20	50.80	46.40	48.00	49.30
Tulia	32.00	31.60	27.00	27.00	32.30	34.50	35.00	37.50	37.90	33.40	32.30	33.00
Tyler	49.70	47.00	46.30	49.00	51.70	52.50	50.00	49.30	51.50	48.15	49.00	49.70
Uvalde	43.60	41.20	39.20	42.35	47.70	46.80	44.00	44.00	48.00	45.50	44.30	44.10
Van Horn	33.50	28.70	23.50	21.70	24.25	25.50	31.70	34.20	37.00	33.00	31.80	33.40
Victoria	52.84	50.71	50.39	53.74	57.99	57.80	55.01	54.33	56.36	51.95	52.31	52.54
Waco	46.22	44.50	40.54	43.34	48.25	45.31	40.15	38.32	42.96	42.43	42.96	44.81
Wichita Falls	38.35	37.23	33.68	36.06	41.68	40.90	35.26	35.57	40.46	38.92	38.12	38.50

Table B2.-Wind Run (miles per day)Adjusted to 2 m. Height.

Station	Jan	Feb	Mar	Apr	May	Jun
Abilene	222.52	237.73	264.36	262.45	245.34	239.63
Amarillo	237.18	255.85	285.74	287.60	267.06	263.33
Austin	166.80	173.75	185.91	180.70	165.06	158.11
Brownsville	215.10	228.54	253.50	263.11	247.74	228.54
Corpus Christi	224.11	242.78	261.46	265.19	239.05	218.50
Dallas	205.38	220.45	239.30	233.64	205.38	197.84
Del Rio	164.34	177.42	203.56	205.43	199.83	212.90
El Paso	145.10	159.09	190.55	192.30	180.06	162.58
Galveston	159.90	162.65	164.03	166.79	158.52	147.49
Houston	157.48	169.00	178.61	176.69	157.48	149.80
Lubbock	220.40	242.44	269.99	271.83	260.81	249.79
Midland	192.19	211.03	237.41	241.18	233.64	231.76
Port Arthur	185.91	194.60	201.55	201.55	175.48	152.90
San Angelo	177.22	187.65	211.97	210.23	194.60	191.12
San Antonio	164.34	175.55	188.62	188.62	183.02	181.15
Victoria	199.73	209.33	220.86	224.70	203.57	184.37
Waco	201.70	212.90	235.31	227.84	203.56	199.83
Wichita Falls	213.01	230.12	254.85	249.14	230.12	230.12

Station	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	205.40	193.99	195.89	207.30	220.61	222.52
Amarillo	240.91	227.84	237.18	239.05	239.05	239.05
Austin	144.21	135.52	137.26	139.00	156.37	158.11
Brownsville	217.02	195.89	178.61	180.53	203.57	205.49
Corpus Christi	216.64	205.43	194.23	194.23	218.50	216.64
Dallas	184.65	167.70	173.35	182.77	201.61	203.50
Del Rio	203.56	190.49	171.81	169.95	158.74	156.87
El Paso	145.10	136.36	132.86	131.11	139.86	138.11
Galveston	135.08	129.57	139.22	141.98	154.38	155.76
Houston	134.43	120.99	132.51	134.43	153.64	153.64
Lubbock	209.38	185.50	194.69	205.71	214.89	216.73
Midland	203.50	188.42	190.31	190.31	195.96	190.31
Port Arthur	130.31	125.10	145.95	152.90	175.48	178.96
San Angelo	170.27	158.11	156.37	161.58	173.75	172.01
San Antonio	169.95	156.87	155.01	155.01	160.61	156.87
Victoria	170.92	161.32	165.16	170.92	188.21	193.97
Waco	192.36	181.15	175.55	179.29	194.23	194.23
Wichita Falls	213.01	197.79	199.69	203.50	216.81	213.01

Table B3.-Mean Monthly Average Temperatures (deg F).

Station	Jan	Feb	Mar	Apr	May	Jun
Abilene	42.80	47.40	56.10	65.35	72.75	80.15
Amarillo	35.40	39.40	46.85	56.70	65.35	74.35
Austin	48.75	52.75	61.50	69.60	75.60	81.30
Brownsville	59.40	62.35	68.75	75.25	79.90	82.95
Corpus Christi	55.15	58.50	65.50	72.45	77.85	81.90
Dallas	43.40	47.90	56.70	65.50	72.75	80.95
Del Rio	50.20	55.00	63.30	71.30	77.25	82.65
El Paso	42.75	48.05	55.05	63.35	71.80	80.40
Galveston	52.70	55.20	61.70	69.25	75.80	81.10
Houston	50.35	53.95	60.55	68.25	74.50	80.35
Lubbock	38.75	43.10	51.20	61.05	69.45	77.15
Midland	42.50	47.10	55.70	64.60	72.75	79.55
Port Arthur	50.90	54.35	61.40	68.90	75.20	80.70
San Angelo	43.70	48.35	58.05	66.95	74.25	79.55
San Antonio	49.35	53.50	61.60	69.35	75.50	82.20
Victoria	52.65	56.10	63.25	70.60	76.50	81.70
Waco	45.25	49.40	58.25	67.05	74.20	81.50
Wichita Falls	39.80	44.65	53.50	63.05	71.20	79.75

Station	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	83.95	83.10	76.00	66.35	54.85	45.45
Amarillo	78.60	77.20	69.70	59.25	46.10	37.60
Austin	84.45	84.70	80.15	71.05	60.85	51.60
Brownsville	84.50	84.50	81.80	75.70	68.65	62.05
Corpus Christi	84.05	84.20	81.00	73.90	65.70	58.35
Dallas	85.30	84.90	77.35	67.15	56.10	46.90
Del Rio	85.15	84.80	79.75	70.70	60.35	52.05
El Paso	82.25	80.05	74.35	64.00	52.40	44.10
Galveston	83.25	83.45	79.95	72.75	64.15	56.40
Houston	82.55	82.25	78.15	69.60	60.50	53.45
Lubbock	79.95	77.90	71.15	61.40	49.85	40.65
Midland	81.95	80.80	73.25	63.95	52.55	44.60
Port Arthur	82.80	82.50	78.50	69.70	61.25	54.25
San Angelo	82.65	81.85	75.40	66.20	55.40	46.00
San Antonio	85.00	84.90	79.25	70.25	60.35	52.15
Victoria	84.05	84.05	79.60	71.65	62.90	55.60
Waco	85.60	85.45	78.60	68.40	57.50	48.50
Wichita Falls	84.95	83.65	73.85	64.55	52.40	42.85

Table B4.-Mean Monthly Minimum Temperatures (deg F).

Station	Jan	Feb	Mar	Apr	May	Jun
Abilene	30.80	35.10	43.30	52.90	61.10	68.90
Amarillo	21.80	26.00	32.10	41.90	51.60	61.10
Austin	38.60	42.10	51.10	59.80	66.50	71.50
Brownsville	49.90	52.50	59.10	66.50	72.00	74.90
Corpus Christi	45.30	48.00	55.30	63.20	69.50	73.40
Dallas	32.70	36.90	45.60	54.70	62.60	70.00
Del Rio	38.50	42.90	50.90	59.20	66.30	71.70
El Paso	29.40	33.90	40.20	48.00	56.50	64.30
Houston	39.70	42.60	50.00	58.10	64.40	70.60
Lubbock	24.60	28.60	36.40	46.70	55.80	64.30
Midland	28.50	32.60	40.20	49.40	58.10	65.70
Port Arthur	41.50	44.40	51.30	59.50	66.30	72.00
San Angelo	30.60	34.70	43.50	52.70	61.10	66.40
San Antonio	37.90	41.30	49.70	58.40	65.70	72.60
Victoria	42.50	45.40	52.80	61.00	67.70	72.70
Wichita Falls	27.60	32.10	40.60	50.30	59.10	68.00

Station	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	72.70	71.70	65.30	54.80	43.40	33.90
Amarillo	65.50	65.30	57.60	46.00	32.50	25.10
Austin	73.90	73.90	69.80	60.00	49.90	41.20
Brownsville	75.70	75.40	73.20	66.10	59.00	52.40
Corpus Christi	74.80	75.00	72.30	63.90	55.60	48.40
Dallas	74.10	73.60	66.90	55.80	45.40	36.30
Del Rio	74.10	73.60	69.10	59.70	49.00	40.60
El Paso	68.40	66.60	61.60	49.60	38.40	30.70
Houston	72.40	72.00	67.90	57.60	49.60	42.20
Lubbock	68.00	66.20	59.40	48.10	36.50	27.20
Midland	68.50	67.50	61.10	50.60	38.90	30.80
Port Arthur	73.70	73.30	69.70	59.20	51.20	44.30
San Angelo	69.10	68.40	64.00	53.60	42.60	33.00
San Antonio	75.00	74.50	69.20	58.80	48.80	40.80
Victoria	74.60	74.20	70.30	60.90	52.40	45.20
Wichita Falls	72.70	71.40	63.90	52.20	40.60	30.80

Table B5.-Percent Possible Sunshine

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Amarillo	70	69	74	76	73	78	80	78	75	77	73	69
Abilene	61	64	70	72	70	78	79	77	70	71	67	62
Austin	48	51	55	54	56	69	75	74	66	64	55	49
Brownsville	41	48	53	57	64	73	80	76	68	65	51	42
Corpus Christi	43	49	54	56	59	72	80	77	68	68	54	43
Dallas	52	54	59	62	58	68	75	73	68	61	56	52
El Paso	77	82	86	88	89	90	81	81	83	84	82	77
Galveston	48	51	56	61	67	75	73	71	68	71	59	48
Houston	44	49	53	56	60	67	69	68	66	63	51	50
Laredo	56	59	57	58	64	72	79	79	73	73	66	59
Lubbock	65	66	73	74	71	76	77	76	71	75	68	65
Midland	65	67	75	78	78	79	78	74	76	72	72	64
Port Arthur	42	52	52	52	64	69	65	63	62	67	57	47
San Angelo	64	67	68	67	66	77	77	78	73	78	74	69
San Antonio	46	51	57	56	56	67	74	74	67	64	54	48
Waco	54	58	60	56	58	71	75	77	71	73	68	61
Wichita Falls	61	64	64	65	66	77	78	79	78	78	72	67

Table B6.-Mean Monthly Precipitation (inches per month).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	1.04	0.90	1.11	2.21	3.35	2.62	2.24	2.29	2.61	2.79	1.13	0.95
Amarillo	0.53	0.56	0.82	1.13	2.75	3.33	2.88	3.04	1.92	1.71	0.57	0.61
Austin	1.77	2.47	1.93	3.23	4.43	3.26	1.89	2.17	3.67	3.12	2.22	2.06
Brownsville	1.32	1.45	0.60	1.56	2.48	2.63	1.65	2.84	5.39	3.16	1.38	1.20
Childress	0.80	0.81	1.19	2.42	3.31	2.96	2.42	1.57	1.51	1.73	0.92	0.44
Corpus Christi	1.51	1.84	1.00	1.95	3.07	3.06	2.22	3.34	5.79	3.28	1.67	1.31
Del Rio	0.41	0.77	0.66	1.94	2.24	1.63	1.49	1.44	2.68	2.41	0.83	0.46
El Paso	0.45	0.44	0.29	0.21	0.25	0.57	1.52	1.24	1.38	0.82	0.32	0.49
Dallas	1.83	2.32	2.46	3.39	5.10	2.61	2.05	1.98	2.88	3.33	1.72	1.51
Galveston	3.13	2.55	2.45	2.67	3.22	3.87	4.46	4.67	5.78	2.81	3.64	3.74
Hereford	0.33	0.37	0.69	0.78	1.63	2.53	1.86	2.17	1.50	1.42	0.49	0.25
Houston	3.57	2.36	3.32	3.71	6.09	4.41	3.79	4.52	5.63	4.58	4.06	3.37
Laredo	0.68	1.10	0.37	1.42	2.04	1.82	0.71	1.59	2.36	1.62	1.09	0.77
Lubbock	0.43	0.56	1.01	1.22	2.86	2.67	2.29	2.23	2.32	2.12	0.67	0.47
Midland	0.47	0.54	0.49	0.86	2.13	1.49	1.66	1.61	2.01	1.57	0.61	0.52
Nacogdoches	3.83	3.55	3.27	5.04	4.32	3.30	2.93	2.40	3.59	3.10	3.96	3.93
Pampa	0.43	0.71	1.07	1.26	3.13	2.86	2.75	2.52	2.05	1.40	0.86	0.53
Pecos	0.41	0.42	0.34	0.50	0.90	1.17	1.00	1.73	2.41	1.04	0.49	0.41
Port Arthur	4.22	3.31	2.77	3.75	4.63	4.49	5.45	5.41	5.60	3.63	4.16	4.85
San Angelo	0.75	0.86	0.83	1.83	2.61	2.06	1.21	1.72	2.88	2.19	0.90	0.61
San Antonio	1.61	1.85	1.49	2.82	3.59	3.10	1.91	2.62	3.84	3.02	2.09	1.40
Stephenville	1.60	1.83	2.27	3.38	4.87	2.77	1.36	1.91	2.71	2.44	1.78	1.51
Temple	2.33	2.76	1.79	3.64	4.02	3.18	1.24	1.62	2.97	3.54	2.07	2.55
Texarkana	3.70	2.89	4.09	4.09	4.34	4.50	3.01	2.80	3.49	3.86	4.71	3.60
Victoria	2.08	2.05	1.74	2.32	4.96	4.36	3.66	3.19	5.63	3.46	2.51	2.13
Waco	1.72	2.14	2.28	3.78	4.58	2.75	1.94	1.89	3.05	2.96	2.14	1.93
Wichita Falls	1.11	1.16	1.70	2.96	4.64	3.33	2.02	2.13	3.20	2.97	1.40	1.28

Table B7.-Mean Monthly Average Humidity (percent).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Abilene	61	60	55	56	61	59	54	56	62	61	62	61
Amarillo	58	55	51	51	69	49	55	60	58	57	58	61
Austin	68	66	64	67	72	70	65	64	68	67	69	68
Brownsville	80	77	75	76	77	76	74	74	76	76	77	79
Corpus Christi	78	76	74	77	80	78	75	75	76	76	76	76
Dallas	68	66	64	66	61	67	60	61	67	67	68	69
El Paso	51	41	33	27	28	30	44	48	50	46	46	52
Galveston	81	79	81	82	79	76	76	75	75	73	78	81
Houston	75	73	72	73	76	76	75	75	77	76	76	76
Lubbock	59	57	50	49	55	56	56	59	61	59	58	58
Midland	57	55	46	45	52	54	52	55	61	60	58	57
Port Arthur	79	76	76	78	79	80	81	81	80	78	79	80
San Angelo	62	59	53	54	61	60	55	57	65	65	64	64
San Antonio	68	66	63	67	71	69	65	64	67	67	67	68
Victoria	76	74	72	74	77	77	74	74	76	74	75	76
Waco	71	69	66	68	71	67	60	60	67	67	71	71
Wichita Falls	66	66	61	62	66	64	56	58	66	65	68	68

Table B8.-Location of Texas A&M University Agricultural Experiment Stations

City	Agency	Telephone Number
Amarillo	Texas A&M University Agricultural Research and Extension Center	806-359-5401
Angleton	Texas Agricultural Experiment Station	409-849-5708
Beaumont	Texas Agricultural Experiment Station	409-752-2741
Beeville	Texas Agricultural Experiment Station	512-358-6390
College Station	Texas A&M University, Soil and Crop Sciences Department, Information	409-845-3041
Corpus Christi	Texas Agricultural Experiment Station	512-265-9201
Dallas	Texas A&M University Agricultural Research and Extension Center	214-231-5362
El Paso	Texas Agricultural Experiment Station	915-859-9111
Fort Stockton	Texas Agriculture Extension Service District Office	915-336-8585
Houston	Texas Agriculture Extension Service	713-855-5600
Lubbock	Texas A&M University Agricultural Research and Extension Center	806-746-6101
Montague	Texas Agricultural Experiment Station	817-894-2906
Overton	Texas Agricultural Experiment Station	903-834-6191
Pecos	Texas Agricultural Experiment Station	915-447-3151
San Angelo	Texas A&M University Agricultural Research and Extension Center	915-659-6524
Sonora	Texas Agricultural Experiment Station	915-387-3168
Uvalde	Texas Agricultural Experiment Station	210-278-9151
Vernon	Texas Agricultural Experiment Station	817-552-2841
Weslaco	Texas A&M University Agricultural Experiment and Extension Center	210-968-5581