

Characterization of the Meteorological Demand for the Design of Vertical Moisture Barriers

M. PICORNELL AND R. L. LYTTON

Pavements founded on expansive soils are damaged because of seasonal wetting and drying of the foundation soils. The magnitude of the damage is controlled by the wettest and driest moisture content profiles that occur at the site. The moisture profiles are altered with the removal or replenishment of soil moisture by the meteorological conditions. Because weather conditions cannot be predicted accurately, the extreme moisture content profiles are stochastic. The purpose of this study is to characterize the wettest and driest moisture content profiles that have the desired probability of occurrence during the lifetime of the pavement. The wettest and driest profiles are associated with the respective annual maximum and minimum depths of water stored in the soil profile. The stored depth of water in the soil profile is obtained by using a daily water balance to calculate the accumulation or depletion of water in the profile. The replenishment is due to rainfall and runoff from the adjacent pavement surface. The depletion of the profile is due to the actual evapotranspiration. The daily water balance is calculated using a consecutive series of annual events. Each year is characterized by the maximum and minimum water depths stored in the soil profile. The fact that both the maximum and minimum depths of stored water have distributions of their probability of occurrence makes it possible to define the probabilistic "design event." The design events are the maximum and minimum water depths that have the desired probability of not being exceeded in the lifetime of the pavement. Illustrated in this paper is this method for the climatic areas of Houston, Dallas-Fort Worth, and San Antonio, Texas.

Pavements founded on expansive soils are damaged because of the seasonal wetting and drying of the subsoil. The severity of the damage is determined by the magnitude of the subsoil moisture change from the wettest to the driest moisture profiles.

The subsoil moisture changes are determined by the climatic conditions at the site. Because weather conditions are unpredictable, the wettest and driest moisture profiles are stochastic. The design moisture profiles are the most extreme conditions that can reasonably be expected to occur during the lifetime of the pavement. These extremes can be evaluated based on the historical record of meteorological data for the site. This permits the determination of the probabilities of occurrence of the annual driest and wettest subsoil conditions. The annual extreme moisture profiles with a return period equal to the design life of the pavement are the design climatic conditions needed to select the minimum depth of the vertical moisture barrier.

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This paper presents a semiempirical approach to evaluating the design intensities of the wettest and driest moisture conditions of the subsoil; describes the statistical analysis used to choose the design extremes; and presents a summary of the results obtained for the regional climatic conditions of San Antonio, Dallas-Fort Worth, and Houston, Texas. These three sites have broader implications for the United States because they are located in a moisture transition zone between wet and dry climates. Design events that are defined for these locations can probably be used for other sites in the wet and dry climatic zones.

CHARACTERIZATION OF THE SUBSOIL MOISTURE CONDITIONS

The aspect that has received most of the attention in the existing literature is the characterization of drought. In some disciplines, like hydrology, and for the earliest climatologists, drought is synonymous with a lack or deficit of rainfall. This aspect is discussed by Blumenstock (1). He determines probabilities of runs of consecutive dry days for different sections of the United States using the criterion that the drought spell is over when a precipitation of 0.1 in. falls in a 48-hr period.

Thornthwaite (2) uses a precipitation-efficiency index to distinguish several types of climate. Based on this index, he prepared maps of the United States (3) and attached probabilities to the occurrence of drought during the growing season. This appears to have been the first attempt to tag a probability to the occurrence of drought (4).

Rainfall is only the input into the soil profile, and a proper characterization of drought should also include how much is being taken out of the soil by evapotranspiration. The first and probably most well-known procedure including both components was proposed by Thornthwaite (5). It considers the potential evapotranspiration (PET), which is determined from the average monthly air temperatures, and proposes a moisture index that compares PET and rainfall on a monthly basis.

All of these earlier procedures are assessed on a monthly basis and they neglect the influence of the soil profile as a moisture reservoir of varying capacity (4). By way of contrast, on a daily basis it is possible to consider the inefficiencies of rainfall, losses as run-off, or evaporation as the soil is depleted and the PET cannot take place.

When the procedure is done on a daily basis, the soil profile is considered as a storage reservoir of soil water, characterized

by the maximum water depth available to plants, from maximum capacity to the point where insufficient water is available to the root system. However, two essentially different alternatives exist. The first one takes the drought as a relative condition (6). Essentially, it considers, for example, that a given weather condition that might be considered a severe drought in the Northeast could be considered a wet period in west Texas. The method developed by Palmer (7) uses an accumulated severity index combined with the length of the dry period. The procedure measures variations from a normal or average condition, and the method can be used to characterize either dry or wet periods.

In the second alternative, proposed by van Bavel (8), drought is considered to be an absolute condition, in which plant growth starts to be limited. In this approach, drought is characterized by the length of persistence of a certain condition or unit of measure: the "drought-day" (4). This is defined as a 24-hr period in which the soil moisture stress exceeds a limit at which the conditions for plant wilting persist. As each growing season is characterized by the number of drought-days, it is possible to attach probabilities to the annual number of drought-days.

In this study, the moisture condition of the subsoil is characterized on the basis of the soil water depth stored in the soil profile. At field capacity, the soil profile is at its maximum capacity. At the point of wilting of the vegetation, the soil profile is considered to be empty of available water; that is, there is no more soil water available for transpiration or soil evaporation. Probabilities are attached to the annual maximum and minimum water depths stored in the soil profile.

This approach requires the determination of the water depth stored in the soil profile on a daily basis. To perform the frequency analysis of drought intensity, it is necessary to analyze the variation of water depth stored in a soil profile through many years of data, whether historical or simulated stochastic data. The simulation is accomplished with a semiempirical procedure to establish the daily water balance. This requires knowledge of the maximum water storage capacity of the soil reservoir and how the water storage changes with the two possible meteorological conditions, rainfall and PET. The replenishment of water with rainfall is estimated with a proposed empirical procedure to assign runoff based on the depth of the rainfall and the status of the soil water at the beginning of the rainfall. The depletion of water is the result of the actual evapotranspiration. This is obtained from the daily PET with a semiempirical method that separates the PET into potential soil evaporation and potential plant transpiration. The actual rate of each component is estimated based on the status of the soil water stored in the profile and the cumulative soil evaporation and plant transpiration.

EXISTING RECORD OF WEATHER DATA

The meteorological data are available on magnetic tapes from the National Oceanographic and Atmospheric Administration (NOAA), National Climatic Center, Asheville, North Carolina. Two tape decks are used: TD-9750 from the Weather Bureau with the daily summary, and TD-1440 from the Airways Surface Observations, which includes hourly or every-third-hour observations.

The data extracted from these tapes are precipitation, percentage of possible sunshine, sky cover, mean daily temperature, mean relative humidity, and mean wind speed. The first task is to prepare a sequential file for each station with all the information organized in daily blocks for consecutive days. The data recorded hourly or every third hour are averaged out to obtain the daily average. The most relevant information missing from the records is the percentage of possible sunshine, which was not reported before January 1985.

TRANSPORTATIONS OF THE RAW METEOROLOGICAL DATA

All of the daily observations except precipitation are combined into a single variable, the PET, through Penman's formula. This expression is the most widely used to estimate daily evaporation and it is regarded as the most reliable (9).

In the past, it was popular to use the method proposed by Thornthwaite (5); however, this procedure calculates PET based only on incoming radiation and ignores the relative humidity of the air. In semiarid climates or in arid transitional zones (10) the relative humidity of the air is a factor as important as or even more important than radiation. Under these conditions, Penman's formula is particularly suitable. Penman's formula (11) estimates the potential evapotranspiration for a well-watered short grass, and it is as follows:

$$ET = \frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} 15.36 (1 + 0.0062 V) (e_s - e_d) \quad (1)$$

where

- ET = potential evapotranspiration in $\text{cal cm}^{-2} \text{ day}^{-1}$;
- Δ = slope of the saturation vapor pressure curve in $\text{mb}/^\circ\text{C}$ at the mean air temperature (mb = millibars);
- γ = psychrometric constant in $\text{mb}/^\circ\text{C}$;
- R_n = incoming net radiant energy available at the evaporating surface in $\text{cal cm}^{-2} \text{ day}^{-1}$;
- G = radiant energy lost into the soil mass by conduction in $\text{cal cm}^{-2} \text{ day}^{-1}$;
- V = the daily average wind velocity in km day^{-1} at a height of 2 meters;
- e_s = mean saturated vapor pressure in mb ; and
- e_d = actual vapor pressure in mb .

The term $R_n - G$ is the energy available at the evaporating surface. The energy lost into the soil, G , is usually neglected (9), and Ritchie et al. (12) have shown that this is negligible until advanced stages of dessication are reached. In this study, G is considered to be zero.

The net radiant energy R_n (13) is calculated from

$$R_n = R_a (1 - \bar{r}) [0.18 + 0.55(n/N)] - \sigma T_a^4 [0.56 - 0.08(e_d)^{1/2}] [0.10 + 8.9 (n/N)] \quad (2)$$

where

- R_a = mean extraterrestrial radiation in $\text{cal cm}^{-2} \text{ day}^{-1}$,
 r = reflection coefficient taken as 0.2 for green crops,
 n/N = percent of possible sunshine hours,
 σ = Stefan-Boltzman constant $11.71 \cdot 10^{-8} \text{ cal cm}^{-2} \text{ day}^{-1}$,
 T_a = absolute air temperature (Kelvin), and
 e_a = actual vapor pressure of the air in mb.

The mean extraterrestrial radiation R_a is a function of the latitude of the site and the day of the year. R_a is found by interpolating published extraterrestrial radiation data (11).

The percentage of possible sunshine hours (n/N) was not reported before January 1965. However, this parameter has been satisfactorily related to mean daily cloud cover by many investigators (14, 15). This relationship on a monthly basis is obtained by fitting a regression line to the simultaneous record of these two variables. In this manner, the recorded data before January 1965 can be included in the analysis.

The saturated vapor pressure is calculated from the mean absolute air temperature through the expression proposed by Richards (16). The slope of the saturation pressure curve, Δ , is obtained by linear interpolation of the published data (17) of the variation on Δ/γ as a function of temperature.

The wind velocity in Penman's formula is the wind velocity at 2 m. The meteorological stations rarely report the wind speed at 2 m. The heights of the measuring instruments are available on the station's annual summaries (16). The wind profile is approximated with a power law function. The exponent has been found to have a typical value of 1/7 in the lower atmosphere under neutral conditions (17). With an exponent of 1/7, the other constant is backfigured from the measured mean wind velocity and the height of the station's measuring instruments.

STOCHASTIC SIMULATION

The design intensity of the subsoil moisture condition is selected based on the relative frequency of occurrence determined on a stochastically generated series of annual events, as it is believed to provide a better estimate of the probability of occurrence than if it is obtained from the frequency analysis based on the historical record alone (18).

The two daily variables that are used to summarize moisture conditions are the rainfall depth and the PET. The stochastic generation used in this study follows in broad terms the procedure proposed by Larsen and Pense (19). The main features are as follows:

1. It accounts for the seasonal periodicity of the climate by considering monthly distributions for the two variables.
2. The occurrence of precipitation is simulated with a first order Markov chain with two states: wet days and dry days.
3. The correlation between precipitation and PET is preserved through using different monthly distributions of Pet for wet and dry days.

A wet day is a day when there has been rain or a trace of rain; otherwise, it is a dry day. The state of one day is assumed

to depend only on the state of the previous day through the monthly transition probabilities. These are experimentally determined probabilities of a wet day following a wet day, and of a dry day following a dry day. The division of days into wet and dry is somewhat arbitrary. Nevertheless, the PETs during wet and dry days are noticeably different at all three sites.

The first task consists of selecting the distributions that fit best to the observed monthly histograms of daily precipitation and PET on wet and dry days. This analysis is performed with the computer program "WEATHER". A FORTRAN listing of WEATHER is presented elsewhere (20). This program examines the time sequence and forms the monthly histograms of precipitation and PET on wet and dry days. At the same time, the program counts the monthly totals of wet days, days with only a trace of rain, and the number of dry days preceded by a dry day and the number of dry days preceded by a wet day. The program also fits a number of theoretical distributions to the observed histograms and calculates the test statistic for a chi-square goodness-of-fit test.

The monthly distributions of precipitation are formed with precipitation amounts higher than a trace (higher than 0.005 in.). The occurrence of trace amounts is summarized by the probability of having trace amounts in wet days, which is determined as the ratio of the number of days with a trace of rain over the total number of wet days. This probability is defined on a monthly basis, and it is assumed to be constant within each month.

The transition probabilities are also assumed to be constant within each month. The monthly dry day transition probabilities were calculated as follows:

1. The dry-dry transition probability is the ratio of the number of dry days preceded by a dry day over the total number of dry previous days, and
2. The wet-dry transition probability is the ratio of the number of dry days preceded by a wet day over the total number of wet previous days.

The monthly wet day transition probabilities were obtained by subtracting the dry day transition probabilities from 1.

The theoretical distribution fitted to the more-than-trace-amount of rainfall is a gamma distribution with an exponent of less than 1, which results in a distribution asymptotic to both the x and y axes in the first quadrant. The parameters of these distributions are calculated using the approximate maximum likelihood estimators of Greenwood and Durand (21).

The monthly distributions of PET are formed separately for dry days and wet days. A beta distribution of zero lower bound is fitted to these data. The upper bound is treated as an additional parameter of the distribution. This upper bound is obtained by successive iterations as the value that minimizes the test statistic. For each iteration, the moment estimators are used to determine the other two parameters.

The stochastic simulation consists of generating a specified number of 1-year events of 365 days. This involves the generation of random observations from gamma and beta distributions. The simulation process is dominated by the first-order Markov chain used to simulate the occurrence of precipitation.

The total number of annual events generated is decided based on the design life of the pavement. In this study, the time

length of the generated sequence is one order of magnitude longer than the return period of the design event. The data are generated with the computer code "STOCHAS", whose FORTRAN listing is presented elsewhere (20).

SOIL-WATER BALANCE

The parameters that intervene in the soil-water balance are the actual infiltration, the actual evapotranspiration, and the maximum water storage capacity of the soil profile. Another variable with a marked effect is the rainfall multiplying factor (RMF), which, as described elsewhere (20), takes into account the runoff from the pavement surface.

The RMF is a function of the cross section of the pavement. The maximum water storage capacity of the soil profile is also a site-related parameter. To cover all possible cases to be encountered in a climatic region, these two parameters are assumed to have a range of values; the RMF is assumed to range from 1 to 5, and the maximum water depth capacity of the soil profile is assumed to range from 20 to 65 cm of water depth. With this approach, the soil-water balance is only a function of the regional climatic conditions and is independent of site-related characteristics.

The rest of this section describes how to obtain the actual infiltration from the rainfall depth, and the actual evapotranspiration from the PET.

Calculation of Infiltration

To formulate the water balance, it is necessary to estimate the portion of the rainfall plus runoff from the pavement that is not used in replenishing the soil profile. A variety of empirical procedures exist (22, 23); most of them assign an empirical rate of runoff based on an antecedent condition and the rainfall depth. The antecedent condition is usually related to the amount of rainfall in a period of several days immediately preceding the event.

In this particular study, the soil-water depth stored in the soil profile is known at all times, and, intuitively, it appears that this should be a much better choice for the antecedent condition than the immediately preceding rainfall. This aspect is evaluated based on hydrologic measurements obtained from a grassed watershed in Riesel, Texas. These data were provided by the U.S. Department of Agriculture, Blacklands Conservation Center, Temple, Texas.

The measurements correspond to the watershed SW-12. This watershed has a typical central Texas swelling clay profile that is covered with native Texas grass. The only cultivation is to mow the grass once a year. The data available include daily rainfall and runoff depths from 1977 through 1982, and approximately biweekly measurements of stored water depth in the profile since the middle of 1979.

The alternative considered is based on the fact that the infiltration is limited to some maximum, based on the water depth deficit of the soil profile at the start of the event. How fast this water deficit can be replenished is a function of the permeability and the sequence of events and rainfall rates. In the case of a swelling soil deposit, there is an additional feature: the shrinkage cracks, which provide some immediate storage of

rainfall independent of soil porosity. Holmes (24) has shown that, upon drying, a soil ped shrinks but it remains essentially saturated down to water potentials of the order of pF 5. This implies that the volume of water lost is approximately equal to the volume change of the soil profile except under the driest conditions. By assuming that the shrinkage is isotropic and infinitesimal, the linear shrinkage is one-third of the volumetric strain. The shrinkage in the vertical direction does not generate storage volume: only the two-thirds in the two horizontal directions cause the shrinkage cracks that provide the storage for the rainfall. Therefore, the maximum storage volume immediately available is about two-thirds of the total volume of the water deficit. This is true for the first rainfall onto a soil profile with empty cracks. But, once the cracks are partially filled, the storage available is no longer the two-thirds of the water deficit but some smaller fraction.

The value of this fraction is estimated from the soil water depth measurements and hydrologic record of watershed SW-12. For this purpose, the soil water depth antecedent to each event is determined by interpolating between consecutive measurements. The rate of water evaporation is assumed constant in each interval. The rate applicable to each period is found by dividing the water loss (initial minus final soil water measured) plus the net precipitation (rainfall minus runoff during the interval) into the total number of days. The complete set of results is described elsewhere (20). The main conclusion is that this fraction ranges from one-third to somewhat less than two-thirds.

The analyses are repeated for two assumptions of the value of this fraction of one-third and two-thirds. The case of one-third is the high runoff case. The case of two-thirds is the low runoff case. Whatever the value adopted, this fraction is considered to be a limit. Precipitation amounts smaller than this limit are assumed to cause no runoff. When the rainfall exceeds it, this limit is the maximum amount of water absorbed by the soil profile; the excess rainfall is runoff.

The total water depth available to replenish the soil profile is obtained by multiplying the rainfall depth by RMF. The need to include the RMF and the procedure to estimate its value are discussed elsewhere (20). The rainfall depth of 0.05 in. is assumed to be a threshold. Below this threshold there is no runoff from the pavement, and thus the RMF is 1. Above this threshold rainfall, there is runoff from the pavement and the RMF is determined from the cross section of the pavement. If the total water depth available is larger than one-third (or two-thirds) of the water deficit of the soil profile, the excess water depth is considered runoff. If the total water depth available is smaller than one-third (or two-thirds) of the water deficit of the soil profile, all the water available is assumed to replenish the soil profile.

Determination of the Actual Evapotranspiration

The accounting of the water removed from the soil profile follows the semiempirical approach of Richardson and Ritchie (9). This is a simplified method to estimate the actual evapotranspiration based on the PET and the stage of drying of the soil profile, accomplished by splitting the PET into a potential soil evaporation and a potential plant transpiration.

The effect of the stage of drying is then evaluated separately for each component.

The potential soil evaporation (E_p) has been empirically related to the PET and the Leaf Area Index (25).

How much of this potential can actually take place (E_a) depends on the moisture conditions at the soil surface and the moisture transmissivity of the soil matrix. Their effect has been considered (26, 27) to take place in two stages of soil evaporation, as follows:

1. The constant rate, or Stage I, when the actual soil evaporation matches the potential; and
2. The falling rate, or State II, when the actual evaporation rate lags behind the potential.

How long the profile remains in Stage I is determined by the cumulative soil evaporation that must remain smaller than a limiting value (U) typical of the soil profile. The cumulative evaporation in Stage I is adjusted on a daily basis adding the soil evaporation and subtracting the effective precipitation. The minimum of this cumulative evaporation is zero, and the effective rainfall in excess of U is not considered to affect it. Once the cumulative evaporation reaches the upper limit U , it remains constant at that value, and the soil profile enters into Stage II of evaporation.

In Stage II, the falling rate of evaporation is estimated following Black et al. (28), who showed that the cumulative evaporation in Stage II is proportional to the square root of time elapsed since the evaporation started on an initially wet soil profile; the constant of proportionality, α , being a function of the hydraulic conditions of the soil matrix.

If the effective rainfall is higher than the cumulative Stage II evaporation, the profile is taken back to Stage I, and the excess rainfall is subtracted from the upper limit U to find the initial cumulative Stage I evaporation. If the rainfall is less than the cumulative Stage II evaporation, then the soil is kept in the Stage II drying, but the time origin is reestimated based on the new cumulative Stage II evaporation.

The values of the soil parameters ($U = 6$ mm) and [$\alpha = 3.5$ mm/(day)^{1/2}] are adopted from Richardson and Ritchie (9) for a typical expansive soil profile in the Texas Blacklands.

Plant transpiration takes place in three distinctive stages of drying of the soil profile. In the first, the transpiration is determined by the atmospheric demand alone. The stage extends from field capacity (a soil water depth of UL), up to a threshold known as the lower limit for potential evaporation (a soil water depth of LLE_0) (29). In the second stage, transpiration is limited by the soil water. This stage extends from LLE_0 to the lower limit of water availability (a soil water depth of LL). In the third stage, plant transpiration ceases altogether.

The actual plant transpiration in the first stage is equal to the potential transpiration. The potential plant transpiration (EP) has been found to depend on the PET and the Leaf Area Index (30).

In the second drying stage, the drop of actual transpiration relative to the potential has been found to be proportional to the square root of time (29, 31).

The last stage occurs when the soil water reaches the water depth LL . This is the minimum water depth attainable. Evaporation and transpiration are assumed to stop when the stored water depth falls to LL .

The actual evapotranspiration (E) is obtained by adding the actual soil evaporation (E_s) to the actual plant transpiration (E_p). If this sum (E) is larger than the PET, the actual evapotranspiration is considered to be the PET.

Formulation of the Water Balance

Soil water is accounted for on a daily basis. The soil water at the end of the day is found by adding the effective precipitation and subtracting the actual evapotranspiration to the soil water that had accumulated the previous day. The soil water depth is not allowed to fall below LL or above UL by neglecting any excess evapotranspiration or precipitation.

The procedure neglects the losses of soil water by deep percolation, or the upward flow from deeper layers. Nevertheless, the permeability of the soil matrix is extremely low, and the assumption of negligible water fluxes in the matrix seems quite appropriate.

The water balance is calculated with the computer program "DROUGHT", whose FORTRAN listing is presented elsewhere (20). The program examines two possible runoff cases: high runoff and low runoff. The program analyzes a sequence of consecutive annual events of 365 days, each keeping an account of the maximum and minimum soil water depths that occurred during each year, and provides a distribution of the relative frequencies for each of the two extreme conditions.

DESIGN EVENTS FOR THREE TEXAS SITES

The design is based on the maximum and minimum soil water depth that is reasonable to expect in the lifetime of the pavement for a desired level of probability. The maximum capacity of the soil profile is treated as a parameter in this study, and the analyses have been performed for a range of soil capacities from 20 to 65 cm in 5 cm increments. The RMF is also treated as a parameter and all of the analyses are repeated for five different values of RMF from 1 to 5. Furthermore, each case considers two alternatives to assign runoff: in the high runoff case, the runoff is computed as all the rainfall exceeding one-third of the water deficit; in the low runoff case, all the rainfall that exceeds two-thirds of the water deficit is assigned to runoff. The low runoff case represents the limiting case; the events defined in this case are the least severe to be expected. The high runoff case is expected to be closer to the field conditions, that is, on the dry side.

The analyses at each site consist of about 25 runs of the program STOCHAS for each assumption of maximum water capacity and case of runoff. One thousand years are stochastically generated for each run. Each series is examined with the program DROUGHT to form the distributions of annual maximum and minimum water depths.

Annual Minimum Water Depths

The complete set of distributions for the three sites has been presented elsewhere (20). These results indicate that the effect of the RMF is to increase the annual minimum water depths. This tendency is consistent for all of the cases studied. For

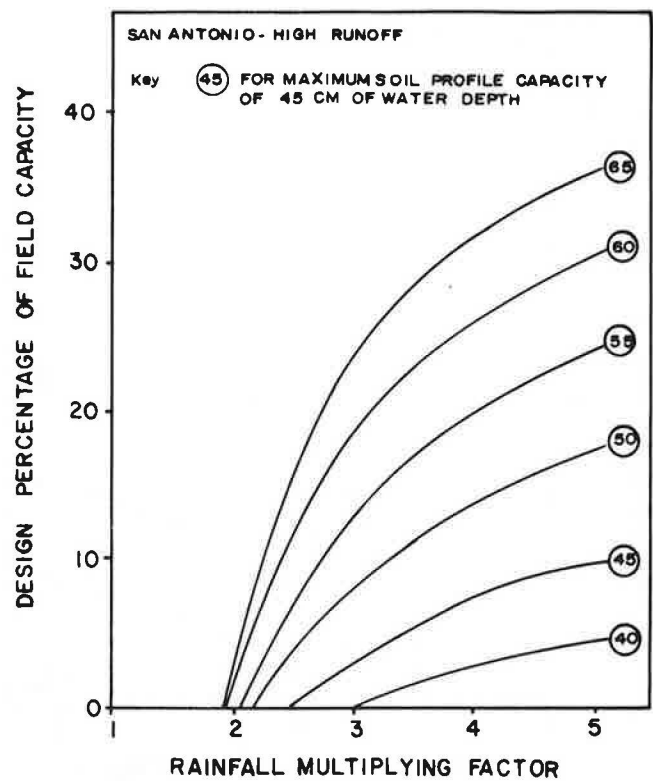
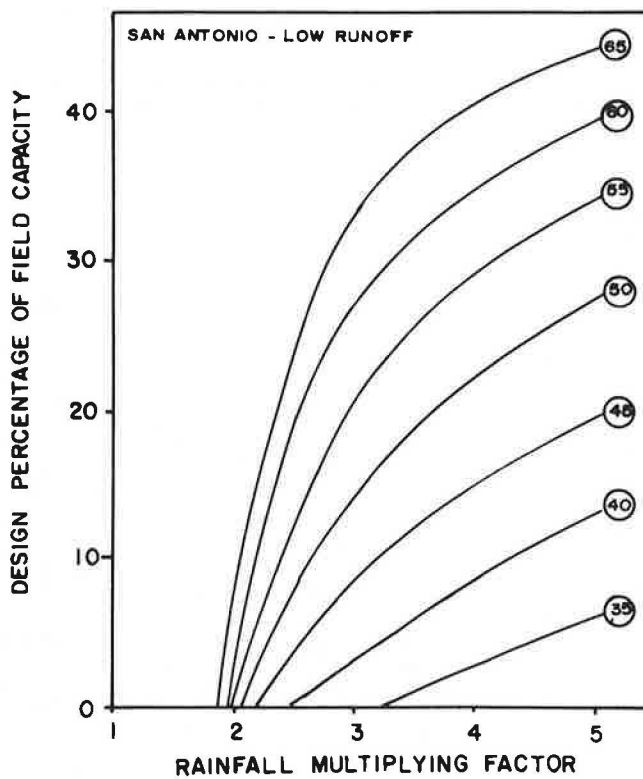


FIGURE 1 Twenty-five-year design events for San Antonio.

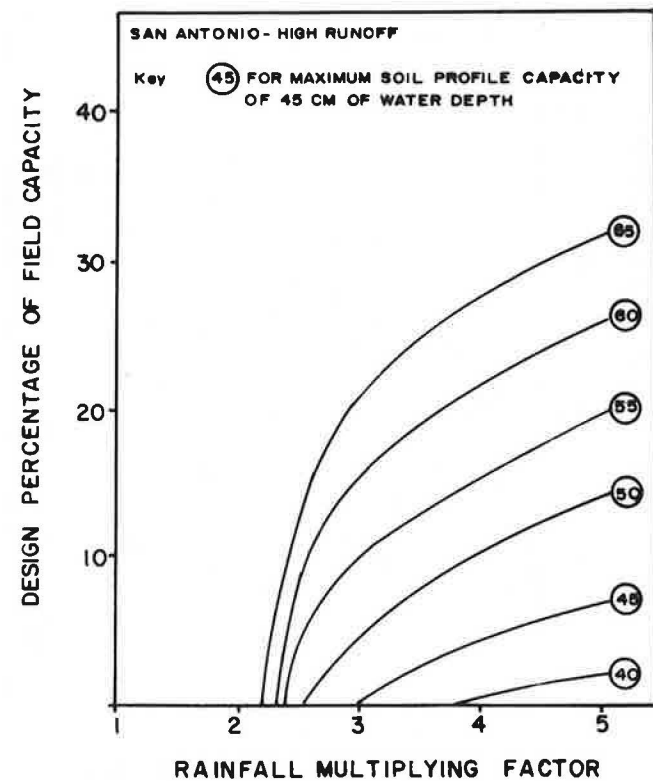
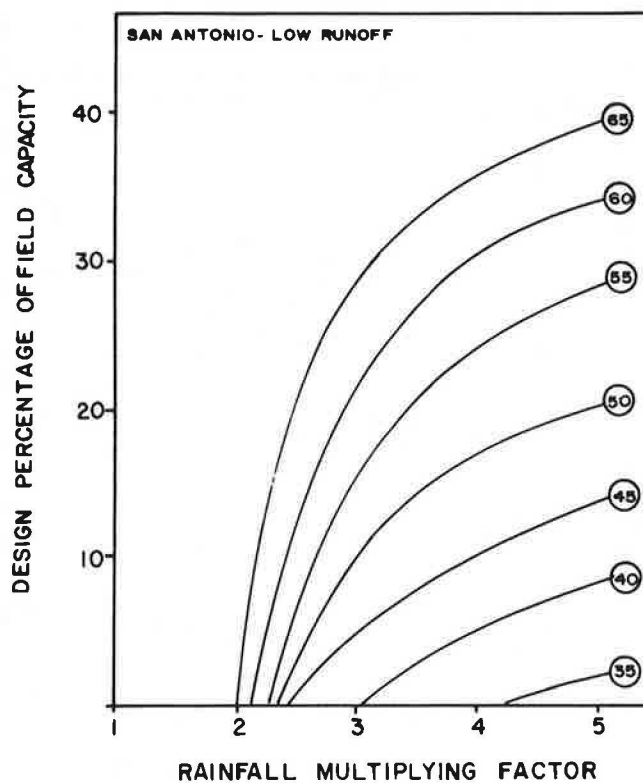


FIGURE 2 Fifty-year design events for San Antonio.

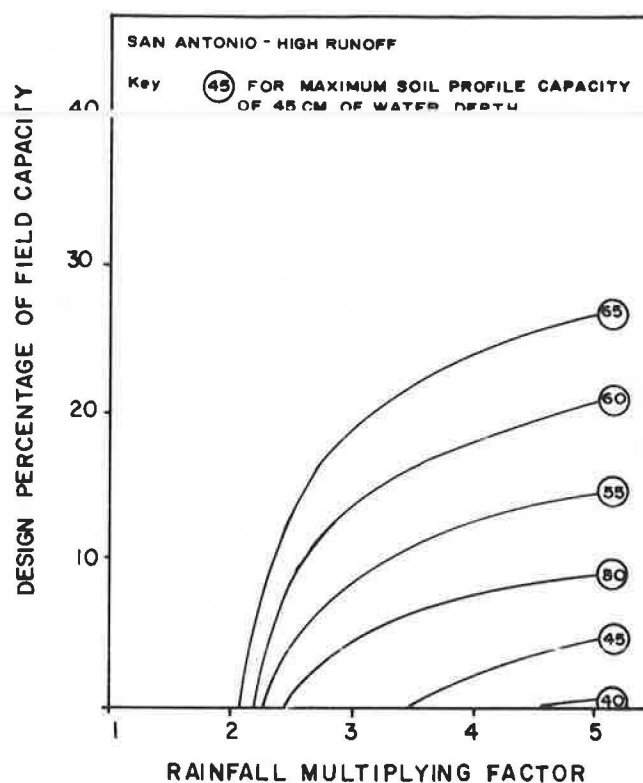
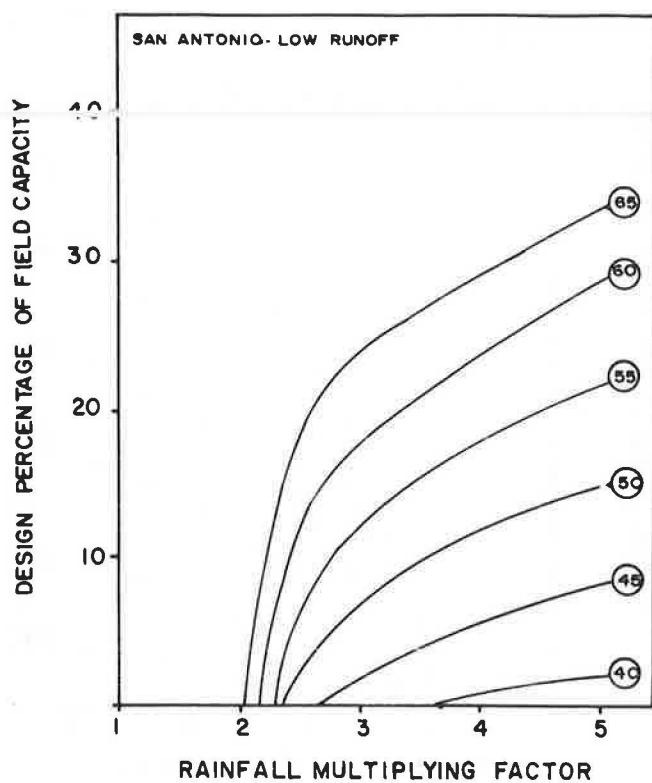


FIGURE 3 One-hundred-year design events for San Antonio.

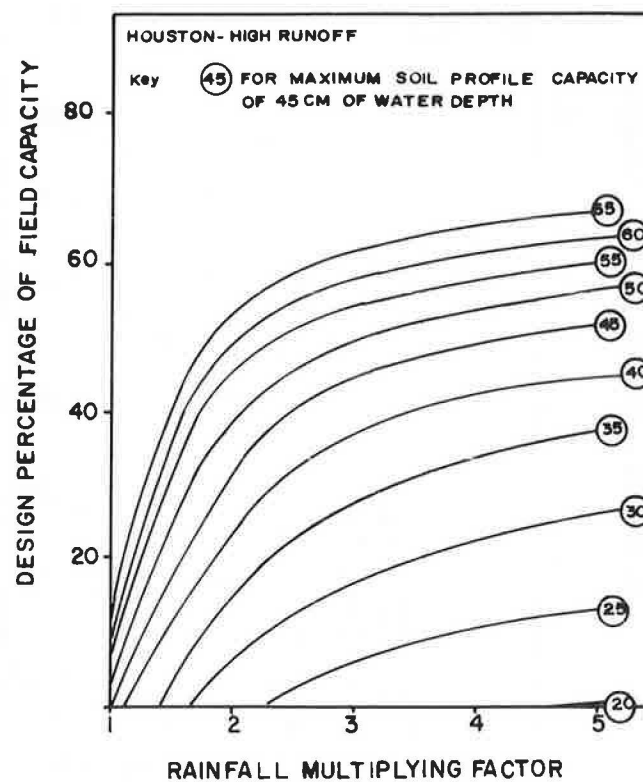
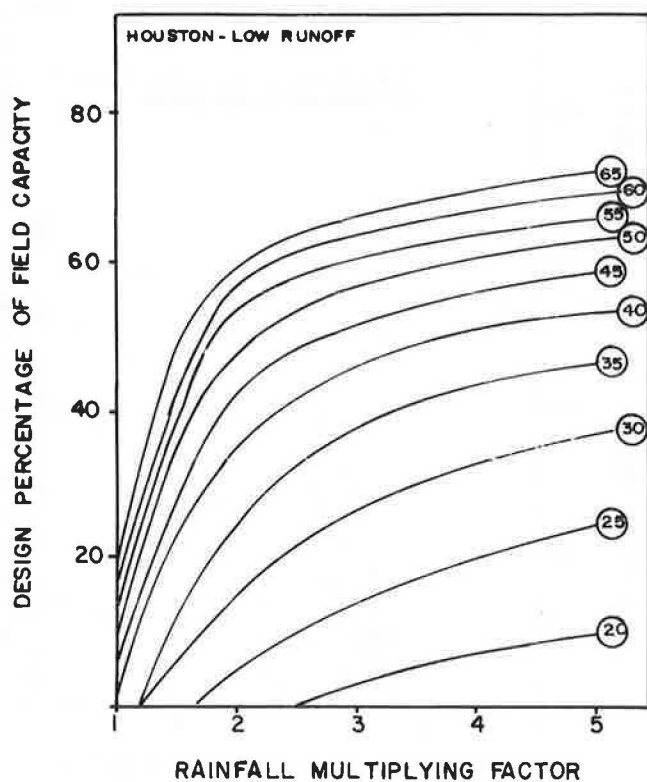


FIGURE 4 Twenty-five-year design events for Houston.

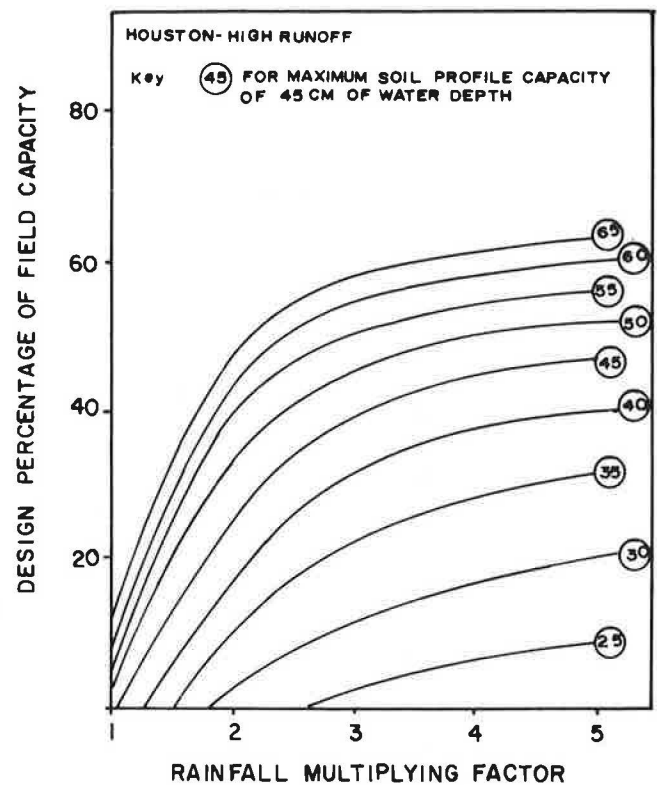
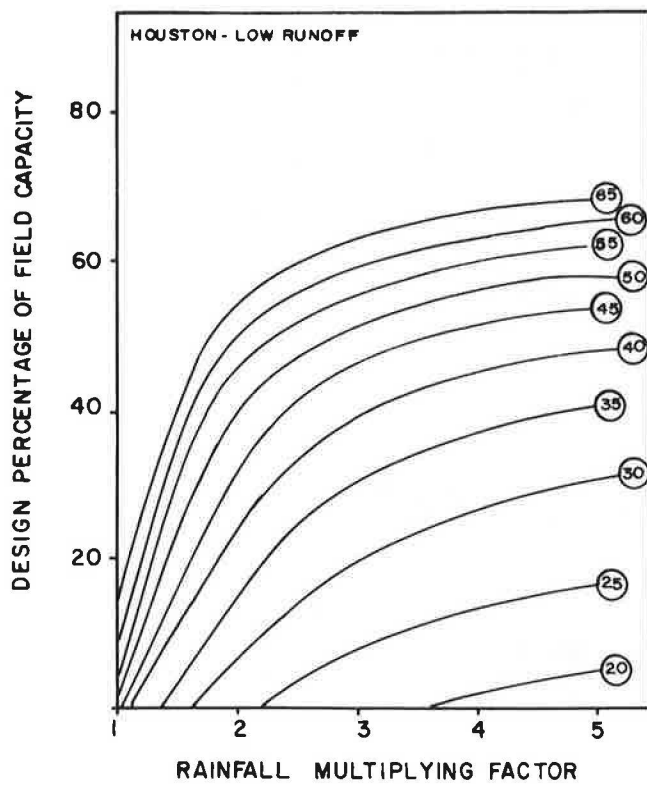


FIGURE 5 Fifty-year design events for Houston.

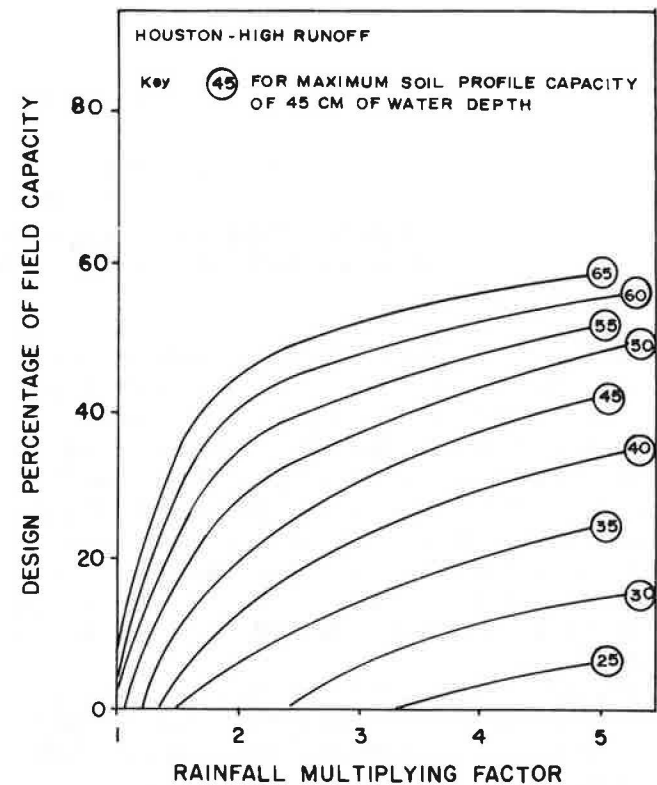
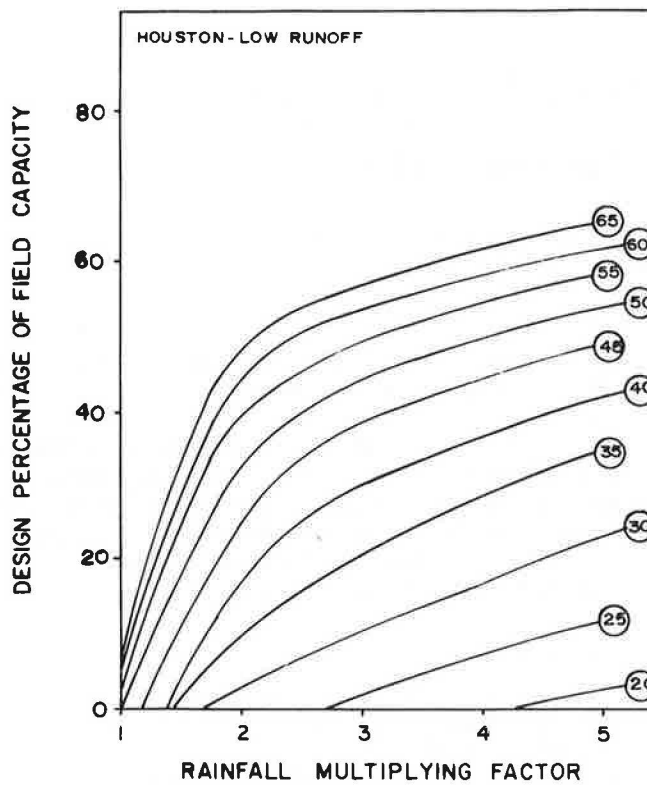


FIGURE 6 One-hundred-year design events for Houston.

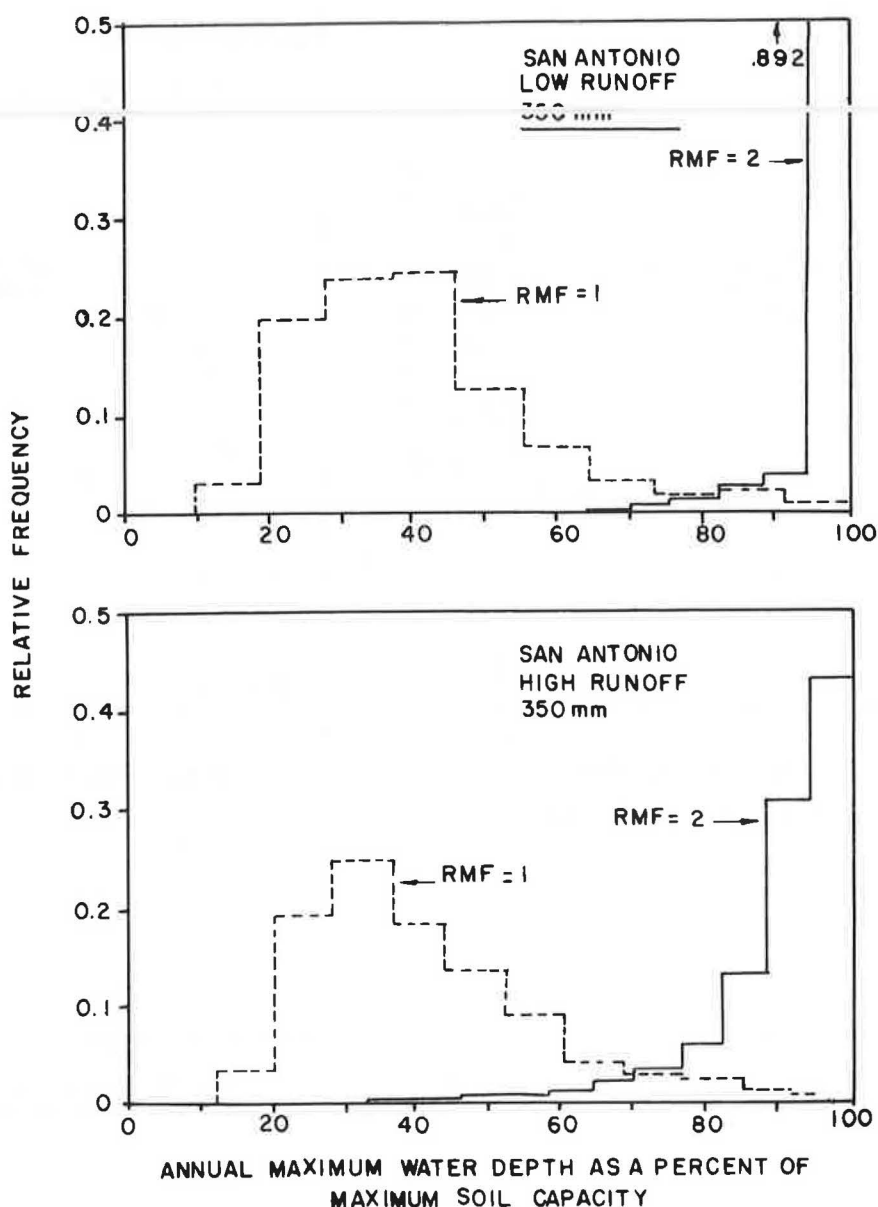


FIGURE 7 Effect of the rainfall multiplying factor on the distribution of annual maximum water depths in San Antonio.

an RMF of 1, the annual minimum water depth is 0 in more than 95 percent of the 1,000 events generated for San Antonio and Dallas-Fort Worth. There is a large increase of the minimum water depth when the RMF increases to 2 in these two areas. The changes associated with an RMF larger than 2 are smaller, though noticeable. The same general trend is also true for the Houston area, but here the changes introduced by increasing the RMF from 2 to 5 are minimal. The annual minimum water depth distribution for Houston with an RMF of 1 is quite similar to those for an RMF of 2 in the other two sites.

Intuitively, it seems that as the soil capacity decreases, the soil will be depleted more frequently. This trend is confirmed at all three sites. Again, the effects in San Antonio and Dallas-Fort Worth are similar; the bell-shaped distributions at high capacities become an exponentially decreasing distribution at

the lower capacity range. The general trend is the same in Houston, but the distributions remain essentially bell shaped over the whole range of soil profile capacities.

The design events were chosen from the distributions of annual minimum soil water depths. Three design events were defined in each site for return periods of 25, 50, and 100 years. The results for San Antonio are shown in Figures 1–3 and for Houston in Figures 4–6. The distribution of annual maximum water depths at San Antonio is illustrated in Figure 7.

REFERENCES

1. G. Blumenstock. *Drought in the U.S. Analyzed by Means of the Theory of Probability*. Technical Bulletin 819, U.S. Department of Agriculture, 1942.
2. C. W. Thornthwaite. The Climate of North America According to a New Classification. *Geographical Review*, No. 21, 1931, pp. 633–655.

3. C. W. Thornthwaite. *Atlas of Climatic Types in the United States, 1900-1939*. Miscellaneous Publication 421, U.S. Department of Agriculture, 1941.
4. C. H. M. van Bavel and F. J. Verlinden. *Agricultural Drought in North Carolina*. Technical Bulletin 122, North Carolina Agricultural Experiment Station, Raleigh, N.C., 1956.
5. C. W. Thornthwaite. An Approach Towards a Rational Classification of Climate. *Geographical Review*, No. 38, 1948, pp. 55-94.
6. W. C. Palmer. Moisture Variability and Drought Severity. *Proc., Thirteenth Annual Meeting of the Agricultural Research Institute*, National Academy of Sciences, National Research Council, Washington, D.C., 1964, pp. 145-157.
7. W. C. Palmer. *Meteorological Drought*. Research Paper 45. Weather Bureau, U.S. Department of Commerce, 1965.
8. C. H. M. van Bavel. A Drought Criterion and Its Application in Evaluating Drought Incidence and Hazard. *Agronomy Journal*, No. 46, 1953, pp. 167-172.
9. C. W. Richardson and J. T. Ritchie. Soil Water Balance for Small Watersheds. *Transactions of the American Society of Agricultural Engineers*, 1973, pp. 12-77.
10. G. P. de Brimchambaut and C. C. Wallen. *Study of Agroclimatology in Semi-arid Zones of the Near East*. Technical Note 56. World Meteorological Organization, Geneva, Switzerland, 1963.
11. H. L. Penman. *Vegetation and Hydrology*. Technical Communication 53. Commonwealth Bureau of Soils, Harpenden, England, 1963.
12. J. T. Ritchie, E. Burnett, and R. C. Henderson. Dryland Evaporative Flux in a Subhumid Climate: III, Soil Water Influence. *Agronomy Journal*, Vol. 64, March-April 1972, pp. 168-173.
13. G. O. Schwab, R. K. Frevert, T. W. Edminster, and K. K. Barnes. *Soil and Water Conservation Engineering*. 3rd ed. John Wiley & Sons, New York, 1979, pp. 60-66.
14. D. A. De Vries. *Solar Radiation at Wageningen*. Mededelingen Land-bouwhogeschool, Wageningen, The Netherlands, 1955, pp. 277-304.
15. J. Kondo. Analysis of Solar Radiation and Downward Long-Wave Radiation Data in Japan. *Scientific Reports*, Tohokou University, Sendai, Japan, Series 5, No. 18, 1967, pp. 91-124.
16. *Local Climatological Data, Annual Summary with Comparative Data*. National Climatic Data Center, National Oceanic and Atmospheric Administration, Asheville, N.C., 1982.
17. W. H. Brutsaert and G. T. Yeh. A Power Wind Law for Turbulent Transfer Computations. *Water Resources Research*, No. 6, 1970, pp. 1387-1391.
18. C. T. Haan. *Statistical Methods in Hydrology*. The Iowa State University Press, Ames, 1979, pp. 289-291.
19. G. A. Larsen and R. B. Pense. Stochastic Simulation of Daily Climatic Data for Agronomic Models. *Agronomy Journal*, Vol. 74, 1982, pp. 510-514.
20. M. Picornell. *The Development of Design Criterion to Select the Depth of a Vertical Moisture Barrier*. Ph.D. dissertation. Texas A&M University, College Station, 1985.
21. J. A. Greenwood and D. Durand. Aid for Fitting the Gamma Distribution by Maximum Likelihood. *Technometrics*, No. 2, 1960, pp. 55-65.
22. *Hydrology*. National Engineering Handbook. U.S. Soil Conservation Service, 1972, Section 4.
23. H. F. Blaney and W. D. Criddle. *Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data*. Soil Conservation Service, U.S. Department of Agriculture, 1957.
24. J. W. Holmes. Water Sorption and Swelling of Clay Blocks. *Journal of Soil Science*, Vol. 6, No. 2, 1955, pp. 200-208.
25. J. T. Ritchie. A Model for Predicting Evaporation from a Row Crop with Incomplete Cover. *Water Resources Research*, Vol. 8, No. 5, 1972, pp. 1204-1213.
26. H. L. Penman. Estimating Evaporation. *Transactions, American Geophysical Union*, Vol. 37, No. 1, 1956, pp. 43-50.
27. J. R. Phillip. Evaporation and Moisture and Heat Fields in the Soil. *Journal of Meteorology*, No. 14, 1957, pp. 354-366.
28. T. A. Black, W. R. Gardner, and G. W. Thurtell. The Predication of Evaporation Drainage, and Soil Water Storage for a Bare Soil. *Proc., Soil Science Society of America*, Vol. 33, 1969, pp. 655-660.
29. C. H. M. van Bavel. Changes in Canopy Resistance to Water Loss from Alfalfa Induced by Soil Water Depletions. *Agricultural Meteorology*, No. 4, 1967, pp. 165-178.
30. J. T. Ritchie and E. Burnett. Dryland Evaporation Flux in a Subhumid Climate: III, Plant Influences. *Agronomy Journal*, Vol. 63, 1971, pp. 56-62.
31. J. T. Ritchie and W. R. Jordan. Dryland Evaporative Flux in a Subhumid Climate: IV, Relation to Plant Water Status. *Agronomy Journal*, No. 64, 1972, pp. 173-176.

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