AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523

BIBLIOGRAPHIC INPUT SHEET

FOR AID USE ONLY

1. SUBJECT CLASSIFICATION	A. PRIMARY	Agriculture
	B. SECONDARY	Irrigation

2. TITLE AND SUBTITLE

Water requirements manual for irrigated crops and rainfed agriculture

3. AUTHOR(S)

Hargreaves, G.H.

4. DOCUMENT DATE	5. NUMBER OF PAGES	6. ARC NUMBER
1975	43 p.	ARC

7. REFERENCE ORGANIZATION NAME AND ADDRESS

Agricultural and Irrigation Engineering, Utah State University,
Logan, Utah 84322

8. SUPPLEMENTARY NOTES (*Sponsoring Organization, Publishers, Availability*)

9. ABSTRACT

Methods for estimating potential evapotranspiration, ETP, from climatic data and from Class A pan evaporation. Crop Evapotranspiration, ET(Crop), is figured from ETP and crop coefficients, KC. Desirable irrigation efficiencies are suggested, leaching requirements are defined, and soil conditions and other factors influencing the amount of water to be applied are described. A procedure is presented for scheduling irrigation using principally mean monthly climatic data. A concept of dependable precipitation is developed and used to relate to moisture adequacy and crop production or in the development of moisture adequacy production functions. Critical periods for moisture stress are given for a large number of crops. A classification of moisture deficits and climate is proposed to be used principally for evaluating precipitation potential for rainfally agricultural. Computer equations are shown for calculating potential evapotranspiration, dependable precipitation, evapotranspiration deficits, and a moisture availability index.

10. CONTROL NUMBER	11. PRICE OF DOCUMENT
PN-AAB-676	
12. DESCRIPTORS	**13. PROJECT NUMBER**
Farm crops Manuals Precipitation Water supply	14. CONTRACT NUMBER AID/ta-C-1103 Res. 15. TYPE OF DOCUMENT

AID 590-1 (4-74)

WATER REQUIREMENTS MANUAL

FOR

IRRIGATED CROPS AND RAINFED AGRICULTURE

by

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Prepared under Support of
United States Agency for International Development
Contract No. AID/ta-c-1103

Utah State University

October 1975

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SUMMARY

Methods are given for estimating potential evapotranspiration, ETP, from climatic data and from Class A pan evaporation. Potential crop evapotranspiration under favorable growth conditions is estimated from ETP and crop coefficients, KC. Desirable irrigation efficiencies are suggested, leaching requirements are defined and soil conditions and other factors influencing the amount of water to be applied are described. A procedure which principally uses mean monthly climatic data is presented for scheduling irrigation.

A concept of dependable precipitation is developed and used to relate to moisture adequacy and crop production or in the development of moisture adequacy production functions. Critical periods for moisture stress are given for a large number of crops. A classification of moisture deficits and of climate is proposed to be used for evaluating precipitation as a potential resource for rainfed agriculture.

INTRODUCTION

A knowledge of crop and plant water requirements is necessary in water resource planning and operation. Meaningful analyses are needed for both rainfed and irrigated agriculture. A means of rapidly evaluating climate and moisture adequacies, including deficits as well as excesses, for various crops, range, and other vegetative production is of particular importance in agricultural development.

Although much has been written on water requirements and many procedures and formulae are available for estimation of plant needs, many of these are of limited application and are unnecessarily complicated. Some procedures which depend upon tables and graphs cannot easily be adapted to computer calculation. The approach recommended in this manual is to relate water use to fundamental relationships that can be readily evaluated either manually or by computer. Methods were selected to permit maximum use of general climatic atlases and other world-wide data sources.

Climatic data are not always collected in the same manner or with the same degree of accuracy. For this reason, it is necessary that wherever possible water requirements be evaluated based upon calculations by more than one estimation method.

Water requirements depend to an important degree upon potential demands and the factors that relate a standardized potential to crop or plant water use. Gross water requirements and the scheduling and timing of irrigation depend upon several other factors including irrigation efficiency, leaching requirements, soil conditions, and the amount, intensity, and distribution of precipitation. These factors are described in sufficient detail so as to provide guidelines for planning, design and operation and maintenance of agricultural development enterprises.

With increasing world population and expanding per capita demands for food, fiber, and other agricultural products, there is an increasing need for a better analysis of moisture adequacy as it relates to efficiency or level of production. Some of the factors influencing a moisture adequacy production function are given and include timing of deficiencies, soil fertility, and crop characteristics.

This manual is designed to give the practicing engineer or agriculturalist the basic procedures for estimating water requirements and moisture adequacies. A minimum of theoretical discussion is presented. Ease of computation, simplicity, and widespread applicability have been given primary emphasis. Whenever computer services are available and sufficient data coverage warrants, computer computation is recommended.

DEFINITION OF TERMS

Potential Evapotranspiration, ETP, is the amount of water evaporated and transpired from an actively growing, short green plant cover (usually grass) with a full crop cover and a continuously adequate moisture supply. It is considered to be dependent upon the climate and can be estimated from climatic parameters, the most important of which are available incoming radiation, ambient air temperature, and relative humidity. The incoming radiation is related to the extraterrestrial radiation that reaches the outer atmosphere and is modified by the factors that influence its transmission through the atmosphere such as cloudiness. These climatic parameters are not independent of each other but are interrelated in a complex manner. Evapotranspiration, as measured by Pruitt (16)[1] at Davis, California, using twenty-foot diameter weighing lysimeters planted to grass, is proposed as standard for potential evapotranspiration.

The ASCE Technical Committee on Irrigation Requirements (1) has used alfalfa as a potential evapotranspiration standard. Potential evapotranspiration from grass, as used in this manual, is about 80 to 87 percent of that from alfalfa.

Actual Evapotranspiration, ETA, is the potential use of water by agricultural crops including direct evaporation from moist soils and wet vegetation. It depends on the climate, the crop, and assumes an adequate soil moisture supply. The climatic factors are considered in the estimation of potential evapotranspiration. Crop factors are used to calculate ETA from ETP and are influenced by the stage of growth, percentage

[1]Numerals in parentheses refer to corresponding items in Appendix I-References.

of ground cover, plant height, and total leaf surface. Evapotranspiration may be limited by soil moisture availability within the root zone by crop diseases and by some crop characteristics. ETA is a potential water use under favorable conditions and is equivalent to ET(crop) as used by FAO in Irrigation and Drainage Paper 24 (6).

Dependable Precipitation, PD, is the precipitation that has a specified probability of occurrence based on an analysis of long-time precipitation records. For irrigation development, a seventy-five percent probability level, or the rainfall that may be expected to occur three years out of four years, has been selected as a reasonable value for most conditions. For some drought sensitive or high value crops, or special conditions, a higher probability level may be more appropriate.

Moisture-availability Index, MAI, is a relative measure of the adequacy of precipitation in supplying moisture requirements. It is computed by dividing the dependable precipitation by the potential evapotranspiration (MAI = PD/ETP). It indicates the proportion of the crop water supply available from dependable precipitation.

Moisture Deficit, ETDF, is the difference between potential evapotranspiration and dependable precipitation. A moisture excess is indicated by a negative deficit. (ETDF = ETP - PD)

ESTIMATING POTENTIAL EVAPOTRANSPIRATION, ETP

Many useful methods have been developed for estimating potential evapotranspiration, ETP. Christiansen and co-workers (2, 4) developed formulae for estimating Class A pan evaporation, EV, and ETP from extraterrestrial radiation, RA, and various climatic data. The ASCE Irrigation Requirements Committee (1) gives methods for estimating ETP based upon alfalfa evapotranspiration, ET (alfalfa). The Food and Agricultural Organization (FAO) of the United Nations (6) summarizes several methods for estimating ETP based upon ET (grass).

Fortunately, climatic elements or measurements are highly interrelated. At a given location most of the variance in ETP can be reasonably predicted from two or more measured or calculated values of common climatic factors. However, no single measurement predicts a high degree of unique variance. Thus, the effect of one variable depends upon how much variation has been compensated for by another variable. For example, if the radiation effect is properly evaluated and weighted in the computation then the effect of relative humidity is not significant. Much of the variance in percentage of possible sunshine and of incident solar radiation can be predicted from relative humidity measurements. In the FAO publication humidity corrections are given for both the radiation method and for the Penman equation. This becomes unnecessary when combination effects of radiation and temperature are allowed to predict the maximum possible amount of variance in ETP.

Temperature and radiation together can be used to effectively predict most of the variance in ETP, 94 percent for the measured 5-day values for ET (grass) at Davis, California, over an 8-year period and 98 percent of the variance for the measured monthly values ($R^2 = 0.94$ and 0.98 respectively). The products of mean temperature in degrees Fahrenheit, TMF, times incident solar radiation in equivalent mm of evaporation, RSM, were calculated for each 5 day period for the eight years (584 periods). Ratios were calculated for measured lysimeter evapotranspiration ET (grass) divided by TMF x RSM. Regression analyses of these ratios do not indicate a significant degree of correlation with relative humidity, wind movement, or other factors. Graphical and computer analyses using lysimeter data from other locations and countries does not indicate improvement from making corrections using factors other than temperature and radiation.

Incident solar radiation, RS, in Langleys per day can be obtained from data and maps given by Lof, Duffie, and Smith (14). Measured data and estimated isolines are presented providing world-wide coverage.

For the estimation of ETP, RS is converted to equivalent mm of evaporation per month, RSM, by correcting for the number of days in the month, DM, and the latent heat of vaporization of water, L. The equation can be written

$$RSM = 10\ DM \times RS/L \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

For most manual calculations the value for L at 20 degrees Centigrade can be used resulting in the equation

$$RSM = (DM \times RS)/58.5 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

The average latent heat of vaporization, L, for a month is calculated from mean monthly air temperature in degrees Centigrade, TMC, or mean monthly air temperature in degrees Fahrenheit, TMF, by means of the equations

$$L = 595.9 - 0.55 \times TMC \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$L = 595.9 - 0.305 \times (TMF - 32) \quad . \quad . \quad . \quad . \quad . \quad (2a)$$

Equation 1 can be used for any time period by substituting any desired number of days in place of DM.

Potential evapotranspiration, ETP, in mm per month can be approximated by use of the equation

$$ETP = 0.004 \times TMF \times RS \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Equation 3 does not correct for the number of days in the month or for the differences in latent heat of vaporization, L. A more exact estimation is given by an equation using RSM which corrects for the number of days and for the actual values of L. The equation can be written

$$ETP = 0.0075\ RSM \times TMF \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The actual value of radiation can be measured directly, however, many radiometers are poorly calibrated and in many areas radiation maps are based upon insufficient data coverage. Values of reported radiation are in many instances lower than actual. For most irrigated areas or areas requiring irrigation, RSM can be estimated with a good degree of accuracy from extraterrestrial radiation in equivalent monthly mm of evaporation, RMM, and the percentage of possible sunshine, S. The equation can be written

$$RSM = 0.075\ RMM \times S^{1/2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Table 1 gives mean daily values of maximum duration of bright sunshine. Equation 5 was derived from 8 years of data at Davis, California, and then evaluated using long term mean values from many locations including those used by Lof, Duffie, and Smith (14). For areas characterized by prevalent overcast, fog, or smog, some reduction in the constant seems desirable. This reduction in extreme cases may be to 0.065.

There is a general relationship between percentages of possible sunshine, S, and mean monthly 24-hour relative humidity, HM, for each climatic region or area. The equation can be written in the form

$$S = A - B \times HM \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (6)$$

with a maximum value of S = 100.

Values of A and B can be obtained from either regression or graphical analyses using the most representative data available. There is considerable scatter in this relationship and large differences in the amount of variance predicted by the regression equations developed in differing climatic zones or types.

Extraterrestrial radiation, RMD, in equivalent mm of evaporation per day is given in Table 2. RMM is equal to RMD x DM. Computer equations for calculating RMM, RSM, and ETP are given in Appendix II - Computer Equations.

Hargreaves (8) proposed the use of an equation for ETP based upon a monthly latitude factor, MF, mean monthly air temperature, and a coefficient for mean monthly relative humidity CH. The equation can be written

$$ETP = MF \times TMF \times CH \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (7)$$

Details of computation of ETP by Equation 7 are given in Appendix-II. Where either radiation or sunshine data are avilable and are considered to be fairly reliable, Equation 4 is recommended as being superior to Equation 7.

Class A pan evaporation, EV, has been widely used as an index for obtaining ETP. EV and ETP respond in differing degrees to the various weather elements. ETP can be estimated from EV and a knowledge of pan exposure and climatic conditions. Coefficicnts can be developed for the effect of wind in kilometers per day, W, mean percent of 24-hour relative humidity, Hm, and for upwind fetch, F, in meters or distance, D, in meters from some given boundary condition. A standard evaporation pan exposure as used herein is defined as a Class A U. S. Weather Bureau pan surrounded by a short green crop for an upwind distance or fetch, F, of 1000 meters or more under conditions of moderate wind (175-420 km/day or 2-5 meters/sec) and medium relative humidity (40-70 percent). For these conditions the average pan coefficient, KP, is about 0.80. ETP is given by the equation

$$ETP = KP \times EV \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (8)$$

For a pan located in a fairly large dry land or fallow area, the standard value of KP for moderate wind and medium humidity is about 0.55. If the location is on a boundary between irrigated and fallow with the irrigated area on the upwind side, KP is about 0.75. Distance downwind from the irrigated area, D, is used to correct the values of KP. Corrections to the standard values of standardized coefficients, KPS, can be estimated from wind in Km/day, W, relative humidity in percent, HM, and fetch, F, or distance, D, by the equation

$$KP = KPS \times CW \times CHM \times CF \text{ or } CD \quad . \quad . \quad . \quad . \quad . \qquad (9)$$

in which

$$CW = 1.15 - 0.0005\ W \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (9a)$$

$$CHM = 0.80 + 0.0033\ HM \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (9b)$$

$$CF = 0.76 + 0.1 \times F^{1/6} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (9c)$$

$$CD = 0.76 - 0.1 \times D^{1/6} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (9d)$$

Values of W are based upon an instrument height of 2.0 meters above the pan. The anemometer may be placed at various elevations above the ground. Wind velocity increases approximately as the 1/4 power of the height above the effective base level.

The ASCE Irrigation Requirements Committee (1) gives crop coefficients for a variety of crops. The most complete data are available for eight common crops. The coefficients are based upon alfalfa potential evapotranspiration, ETP (alfalfa). The Committee (1) defines ETP (grass) as 80 to 87 percent of ETP (alfalfa). The values given by the Committee were multiplied by 1.20 in order to produce crop coefficients applicable to ETP (grass). Crop coefficients presented by the ASCE Committee (1) times 1.20 are given in Table 3. These coefficients cover the full range of growth stages and are typical of usual irrigation frequencies and normal practices. Table 4, reproduced from Hargreaves (8) summarizes additional generalized crop coefficients, KC, based upon experimental data available from several states and countries.

The FAO Irrigation and Drainage Paper No. 24 (6) presents one of the most complete discussions of crop coefficients. Table 5 gives FAO's seasonal values of ET (crop) for most of the more common field, vegetable, and fruit crops. The seasonal value is also shown as a percentage of ET (grass) for a 12 month growing season. Various field and vegetable crops can be double cropped bringing the total annual use closer to ET (grass). Figure 1 shows FAO's crop coefficients graphically for a variety of crops.

During the initial stage between planting and crop emergence the crop coefficient, KC, depends upon the frequency of soil wetting and upon other factors of lesser importance. Figure 2, reproduced from the FAO paper, gives average values of KC during this initial stage as a function of ETP and frequency of irrigation or rain. The crop coefficients for mid-season and at harvest are given in Table 6.

Although crop coefficients are best defined by curves, showing the values from planting to maturity, they can be approximated by straight lines. Figure 3 presents an example. The use of straight line representation of values of KC permits computer water balance record keeping and facilitates irrigation scheduling.

IRRIGATION EFFICIENCY

Water cannot usually be applied uniformly over the area irrigated. For furrow irrigation infiltration is usually greater at the beginning or head of the furrow. The uniformity of sprinkler irrigation application depends upon wind conditions, the sprinkler pattern, and the spacing of the sprinklers and laterals. In the design of some systems the application is calculated to provide adequate amounts to those areas receiving a minimum amount of water.

Irrigation efficiencies have been variously defined. Overall efficiencies include conveyance and storage. Consideration is herein given to the application efficiency or unit irrigation efficiency. The ASCE Committee (1) defines unit irrigation efficiency as the ratio of the volume of irrigation water required for beneficial use to the volume of water delivered to the area. Israelsen and Hansen (12) define application efficiency as the ratio of the water stored in the soil root zone during irrigation to the water delivered to the farm.

Some operational problems are related to the design and construction of irrigation systems. Canals and sprinkler systems should be designed for full time operation and should have sufficient capacity to provide adequate applications during peak use periods. Irrigation system design should be based upon an efficiency of 60 to 80 percent for surface irrigation and about 80 percent for both sprinkler and drip irrigation systems. High irrigation efficiencies are seldom achieved with systems designed on the basis of low efficiencies, because they provide more water than necessary. Lack of adequate capacities to meet peak demands results in reduction in yields, particularly if water shortages occur during critical periods in the vegetative cycle.

LEACHING REQUIREMENTS

Evapotranspiration removes pure water from the soil solution thereby concentrating the remaining salts. Since all irrigation waters contain some salts, some leaching is required to prevent an increase in the salt concentration of the soil solution in the root zone soil to levels unsuitable for crop growth. For leaching to occur, the soil profile must be well drained, either naturally or artificially. Leaching is frequently accomplished by rainfall. If rains periodically flush excess salts from the soil profile, no extra water allowance needs to be made for leaching when irrigation requirements are calculated.

Under specific irrigation conditions, salts may precipitate in the soil or may dissolve from precipitated minerals. Three common natural salts (listed in order of solubility), $CaCo_3$, $MgCO_3$ and $CaSO_4$, will precipitate before the soil solution reaches a concentration that is harmful to most plants. When the quantity of these salts is subtracted from the total present in the soil solution, the remainder is the effective salinity, ES. The remaining soluble salts are the ones that can create a salinity concentration in the soil that is harmful to plants.

Leaching requirements are normally estimated from the electrical conductivity, EC, of the irrigation water. This falsely assumes that the salt present in the water remains in the soil solution. The leaching requirement, LR, in percent of water applied based on this assumption is given by the equation

$$LR = 100 \times EC_{iw}/EC_{ss} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where EC_{iw} is the electrical conductivity in mmhos per cm of the irrigation water and EC_{ss} is the maximum allowable conductivity of the soil solution at the bottom of the root zone or of the drainage water.

Crops vary in salt tolerance. The maximum permissible average salinity in the soil solution at the bottom of the root zone as measured by electrical conductivity, EC, is about 36 mmho per cm for Bermuda grass, tall wheat grass and barley, 32 mmhos/cm for cotton and sugar beets; and from 4 to 16 mmho/cm for most other crops. One mmho is equivalent to about 640 ppm or 10 milliequivalents per liter in the soil solution. The EC of the soil solution is about three times the equivalent electrical conductivity of a saturation extract, EC_e. Methods for determining soil and water salinity are given by Richards et al. (17).

Chemical analysis for water quality consists of determination of the cations and anions (positive and negative ions) which combine to form the natural salts. Principal cations of interest are: Calcium, Ca^{++};

magnesium, Mg^{++}; sodium, Na^+; and potassium, K^+. The principal anions are: bicarbonate, HCO_3^-; sulfate, SO_4^-; chloride, Cl^-; and nitrate, NO_3^-. Other ions are usually present in negligible amounts. Potassium and nitrate are both important plant nutrients, but are usually present in much smaller amounts than the other ions and frequently are not included in the analyses. When expressed in milliequivalents per liter, me/l, the sum of the cations in a soil solution or water sample should approximately equal the sum of the anions.

Of the cations, sodium is considered to be the most detrimental to soil structure and most objectionable. For most crops the sodium ion should not exceed 40 me/l at the bottom of the root zone. On this basis the sodium leaching requirement, SLR, as a percentage of the water required can be expressed by the equation

$$SLR = 100 \times Na^+/40 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (12)$$

An approximate upper limit for effective salinity is about 80 me/l. Based on ES, the leaching requirement equation can be written

$$ESLR = 100 \times ES/80 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (13)$$

Using values from water analyses, SLR and ESLR can both be calculated and the larger of the two values used. A computer program has been developed by Professor Christiansen at Utah State University for making these and other water quality analyses computations. Christiansen (3) proposed the use of the following table for evaluating irrigation water quality:

Evaluation Rating	EC mmhos	Na^+ %	SAR	Na_2CO_3 meq/l	Cl^- meq/l	ES meq/l	Boron ppm
1	0.5	40	3	0.5	3	4	0.5
2	1.0	60	6	1.0	6	8	1.0
3	2.0	70	9	2.0	10	16	2.0
4	3.0	80	12	3.0	15	24	3.0
5	4.0	90	15	4.0	20	32	4.0
6	Higher than limits for 5						

A rating of 1 is excellent for agricultural use. A water rated 6 with respect to any single factor is generally considered unsuitable for irrigation, however, tolerance varies with crops and the effectiveness of drainage conditions.

Emphasis usually is given to maintaining a favorable salt balance or the removal of as much salt in the drainage water as enters in the irrigation water. This prevents salinization of the soil. However, each situation needs to be analyzed. Total salinity and effective salinity of the irrigation water and the upper limit for sodium need to be evaluated. Calcium carbonate, magnesium carbonate, and calcium sulphate precipitate as the soil solution concentration is increased. Successful agriculture could include practices that provide for a temporary salt build up within reasonable limits providing there is the prospect of periodic flushing or the importation of better water in the future.

Salt build up is frequently more the result of poor drainage than from under application of irrigation water. Normal irrigation efficiencies are such that a favorable salt balance can usually be maintained if subsurface drainage is well developed.

SOIL CONDITIONS

Moisture availability to crops depends on the amount and frequency of rainfall or irrigation, the moisture holding capacity of the soil, the osmotic potential and the depth of rooting of the crop. Ideally, rainfall or irrigation should occur in amounts and at frequencies such that soil moisture in the root zone of the crop is always adequate. Some soils are almost uniform in texture and other characteristics to depths of two meters or more. Other soils are highly stratified with barriers to water movement and root development which restrict rooting depths to 30 cm or less, even for some normally deep rooting crops such as alfalfa.

In some instances, the rooting depth of crops depends on the chemical characteristics of the soil as well as soil physical characteristics. For example, in a study of three oxisols (soils with high oxic concentrations, but no visible stratification throughout the normal soil profile), corn and similar crops had rooting depths limited to about 30 cm, and resulting available soil moisture capacities of only 36 to 60 mm, Wolf, (21). Under these conditions, corn wilted after about 6 days without rain. Although mean monthly rainfall may appear adequate, low values of dependable rainfall and frequencies of drought periods of 10 days or more may result in soil moisture deficiencies.

In terms of available moisture-storing capacity in the root zone, soils may vary from about 25 mm (1 inch) of avialable moisture to more than 200 mm (8 inches) depending on the rooting depth of the crop and the soil characteristics.

For soils and crops where avialable soil moisture storage is adequate to supply the requirements for two weeks or more, short drought periods are of lesser importance. Under these conditions a moisture availability index, MAI, (see Definition of Terms) can be expected to have a good correlation with crop production.

SCHEDULING IRRIGATION

The water holding capacity of soils varies with texture, structure, and chemical composition. For irrigation purposes, water holding capacity is considered to be the difference between the field capacity and the wilting point. Various publications give average values of field capacity and wilting point for different textures. The soil reservoir, SR, as used herein, is the approximate depth of available moisture in mm held in the soil per meter of depth. Approximate values of the soil reservoir are about as follows:

Soil Textures	Soil Reservoir, SR
Heavy (clay soils)	165 to 210 mm/meter
Medium (loam soils)	125 to 165 mm/meter
Light (sandy soils)	85 to 125 mm/meter

Multiplying the rooting depth by the soil reservoir gives the total amount of water available to crop plants. Most crops produce maximum yields if irrigated when approximately 50 percent of the soil reservoir is depleted. Some crops, principally the vegetable crops, have shallow or skeletal root systems. These include potatoes, lettuce, onions, strawberries, and others. Such crops frequently yield better if irrigated at 30 percent SR depletion. Table 7 from Griffin and Hargreaves (7) gives effective root depths and suggested percent SR depletions. These values are generalizations and should be modified with more accurate values whenever possible.

From the effective root depth, the soil moisture reservoir and the allowable SR depletion, the effective soil reservoir, ESR, in mm of moisture can be estimated. Dividing ESR by the crop water use in mm per day gives an estimate of the interval between irrigations.

The procedure for estimating the period between irrigations is presented in an example. The following conditions are assumed:

Period	First 5 days of July
Crop and stage	Corn at full crop cover
Root depth	1.30 meters
SR depletion	50 percent
Soil texture	Heavy (clay with SR of 165 mm/meter)

The effective soil reservoir, ESR, is 165 x 1.30 x 50 percent or 107 mm. If from Equations 4 or 7 the potential evapotranspiration, ETP, is 7 mm per day and the crop coefficient is estimated to be 1.15 from Table 4, the resulting ETA is 8 mm per day. If the probable dependable rainfall for July is low enough that it can be neglected, then 107 mm divided by 8 mm per day results in an estimated 13 days between irrigations. If significant rainfall occurs during the period, the interval could be extended or the next irrigation application reduced in amount.

During the germination period and the early growth stage best results for some crops are obtained if the surface soil is kept almost continually moist. Modifications are frequently made in irrigation methods and in irrigation frequency in order to supply these favorable conditions.

Local climatic variations cause variations in actual ET. If the actual temperature and/or radiation are greater or less than the average used, then the irrigation interval can be modified. Hot dry windy weather can have a significant effect on water use, particularly where fields are small and are surrounded by non-irrigated land.

In Mediterranean-type climates precipitation during December, January, and February is frequently adequate to fill the soil reservoir and to provide for the required leaching.

Griffin and Hargreaves (7) propose the scheduling of irrigation through the use of smooth curves showing the monthly potential evapotranspiration factors graphically. Using such data, the daily ETP rate can be estimated as the average for any time period.

Irrigation scheduling can be readily accomplished by computer. Monthly data are frequently more readily obtained than are daily climatic data. A methodology for obtaining approximate daily rates of use from monthly data can be readily adapted to computer computation. Monthly values of ETP are calculated. These are assumed to be representative of the rate of use on the 15th day of the month. It is further assumed that each month can be divided into six periods having approximately equal rates of use during each day of the period. Rates of use for these six periods of approximately 5 days each are calculated from the mean monthly use rate, MMR, and a correction for the difference between the mean use rate for the month and the mean use rate for the previous month, RPM, or for the last half of the month, the difference between the use rate for the next month, RNM, and that for the current month, MMR. The procedure can be written:

First period rate = MMR - 5/12 (MMR - RPM)
Second period rate = MMR - 3/12 (MMR - RPM)
Third period rate = MMR - 1/12 (MMR - RPM)
Fourth period rate = MMR + 1/12 (RNM - MMR)
Fifth period rate = MMR + 3/12 (RNM - MMR)
Sixth period rate = MMR + 5/12 (RNM - MMR)

This procedure gives satisfactory results except for those months in which the rate increases to a maximum and then decreases or decreases to a minimum and then increases. These months are called turn-around months and are usually January and July in the northern hemisphere. For these turn-around months the rate for all periods is assumed equal to the monthly average.

Long term monthly averages of climatic data are available from several sources mentioned above. These publications present world-wide coverage and permit the calculation of potential evapotranspiration and irrigation requirements at representative locations in most countries of the world. Generally, the number of stations provides adequate data for fairly good studies. By use of the computer programs given, a study can be made in a short period of time for a given area. Irrigation can be scheduled based upon long term mean data and then the irrigation schedules modified based upon actual climatic departures from normal conditions.

It is proposed that the methodology given above be used to develop local irrigation scheduling manuals based on long term mean data for each country or area where irrigation is of importance. The manuals should include mean daily potential evapotranspiration for approximate 5-day periods for each location within the country for which climatic data are available.

Actual data for a given period of time are more representative than long term averages. However, in many locations, differences from average conditions are normally not great and large differences are relatively infrequent. ETP depends upon both radiation and temperature. More often than not, increased radiation is associated with increased temperatures, but in many cases air mass transfer reduces air temperatures and thus tends to cancel the effect of the increase in radiation.

DEPENDABLE PRECIPITATION

The U.S.D.A. Economic Research Services and the Environmental Science Services Administration (19) published monthly precipitation probabilities for the 23 Eastern States. Similar studies have been made for various other areas or countries. Dependable precipitation, PD, (see Definitions) can usually be statistically expected with a good degree of accuracy from mean precipitation, PM. The equation can be expressed in the form

$$PD = A + B \times PM \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

in which PD and PM are expressed in mm or in inches. The average values from regression analyses of the 13 Southeastern States of the U.S. are A = - 23 mm or - 0.91 inches and B = 0.84. For much of the more favorable rainfall distribution in Latin America values of A = -10 mm or -0.4 inches and B = 0.70 can be used. Since rainfall cannot be negative, PD has a minimum value of zero.

For areas where the rainfall is less predictable, the slope factor in the equation may be much lower. For the ten states of the Brazilian Northeast, for example, the slope factor, B, varied from 0.42 to 0.74 and the constant, A, or the intercept, from -6 to -36 mm in the best fit regression equations which had R^2 values of 0.62 to 0.90, Hargreaves (9). The lower percentage of variance predicted (lower values of R^2) were from states having two distinct types of climate. Useful relationships which facilitate the estimation of dependable precipitation, PD, from mean precipitation can be developed for any area or type of climate.

The World Meteorological Organization (22) gives mean precipitation for a 30 year period (1931-1960) and several probability levels including the 79 and 60 percent probabilities of occurrence. Data coverage and probabilities are usually adequate for determining the appropriate values of A and B to be used in Equation 14.

The range in relationships found indicate that the 75 percent probability of rainfall occurrence is a much more reliable indication of moisture available for crop production than is mean precipitation. In the 23 eastern states and in most of Central America, Colombia, and Ecuador, a mean monthly precipitation of 100 mm indicates that three years out of four a precipitation of 60 mm or more can be anticipated. For the northeastern states of Brazil a mean monthly rainfall of 100 mm indicates a dependable precipitation of only 25 to 50 mm.

In order to relate precipitation to crop production it seems desirable to evaluate rainfall at a given level of probability and relate dependable supply to potential water use. The concept of a moisture availability index, MAI, (MAI = PD/ETP, see Definition of Terms) was developed for this purpose. This concept could also be considered as a moisture dependability index.

For shallow rooted crops and for soils with low moisture holding capacities, the dependable precipitation may not always be a reliable indication of adequacy of rainfall because of the frequency of drought periods of 10 days or more. For some crops and under some conditions a different probability of precipitation occurrence would seem desirable. For bananas, a deficiency with a probability of occurrence of one in four would not be economically desirable. It seems probable that use of a higher MAI for such crops would result in a satisfactory index. For most crops a deficiency in any one month, with a probability of one year in four, if not preceded or followed by a deficient month, would not result in large economic losses.

Allowable deficiencies are also related in some degree to land values and development costs. Where land values and other production costs are high and water is relatively inexpensive, there is less justification for allowing deficiencies. The converse is also valid. It would seem desirable that additional work be completed on the economics of various levels of moisture deficiencies for specific crops.

MOISTURE AND CROP PRODUCTION

Mirnezami (15) made a study of the relationship of moisture availability and yield of dry farmed wheat in Iran. Values of MAI were generally in the range of 0.20 to 0.53. For the unfertilized trials regression equations were developed for yield as a function of MAI, of ETDF, and of PD, on both an annual basis and a seasonal basis. In each case the coefficient of correlation, R, was 0.93 or higher. If MAI can be taken as an index of moisture adequacy, this correlation indicates a good straight line relationship between yield and moisture in the range of 20 to 53 percent of adequacy.

At the lower values of MAI on an annual basis, MAI of 0.35 and lower, there was no response to fertilization. Yields of fertilized wheat averaged slightly less than the unfertilized. At higher moisture levels (MAI of 0.40 or above) fertilizer application produced very significant increases in wheat yields.

In general, it is difficult to obtain crop production data related to various levels of moisture adequacy. Sometimes irrigation is reported but records of initial soil moisture and growing season rainfall are omitted. Procedures for determining the degree to which moisture is adequate or deficient have not been well standardized. Usually only a portion of the full range of moisture adequacies is correlated with yields. Yield data are presented in a wide variety of units.

Hargreaves and Christiansen (10) summarized yield and water use data from a variety of sources. Available moisture was either calculated or estimated to include moisture stored in the soil at the beginning of the growing season plus growing season precipitation and irrigation water. Yield data were used from Hawaii, California, Utah, Israel, and other locations. Principal crops studied were sugar cane, alfalfa, corn, and forage crops. Some data for potatoes, peas, and sugar beets were also used.

Not all crops are equally sensitive to moisture stress. The timing of moisture deficiencies may play an important role. Adequate moisture is of greater importance during the flowering, fruiting, and fruit or grain sizing stages than at other times in the growth cycle.

Stewart, Misra, Pruitt, and Hagan (18) show that for corn and grain sorghum, the timing of water deficiencies is of great importance. For corn seasonal grain yield is shown to be an inverse function of ET deficits during the pollination period. However, this effect is modified significantly by previous deficits of "conditioning." Production functions are shown as percent yield reduction/percent ET deficit. Seasonal ratios are presented as well as ratios for the major growth periods. Critical periods for soil water stress for different crops are given in Table 8.

For crops such as sugar cane, alfalfa, and forage, recovery from short periods of moisture stress is frequently good. If cell division is not seriously retarded cell enlargement can often catch up during a later period of moisture adequacy. Also for soils with good moisture storage capacities there is a tendency towards a reduction in the adverse effects of poor distribution of rainfall or water applications.

Downey (5) shows a fairly lineal relationship between yields of non-forage crops and mean moisture stress in the root zone. Yield as a percent of maximum is plotted as a function of ET as a percent of that giving maximum yield for 14 non-forage crops. Much of the scatter is attributed to growth stages susceptible to water stress.

In order to standardize the data and to compare the results from different crops, Hargreaves and Christiansen (10) used a procedure similar to that proposed by Downey (5). Y was used to express a ratio of yield to the maximum yield under the prevailing fertility and cultural conditions and X as the ratio of the actual moisture available during the crop season to the amount for which the yield is a maximum. The real values of Y vary from 0 to 1.00 and of X from 0 to 1.00 or more.

Most of the yield data analyzed indicated a relationship that can be expressed by the equation:

$$Y = 0.8X + 1.3X^2 - 1.1X^3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (15)$$

Good data coverage was available for the range of $X = 0.35$ to $X = 1.00$.

The incremental change in yield with change in water availability is given by the first derivative. This can be written:

$$dY/dX = 0.8 + 2.6X - 3.3X^2 \quad . \quad . \quad . \quad . \quad . \quad . \qquad (16)$$

For the range $X = 0.086$ to $X = 0.701$, dY/dX is 1.00 or more with a maximum value of 1.31 at $X = 0.394$. If it is assumed that Equation 15 provides a good representation of the moisture adequacy-yield relationship, then maximum increase in production per unit of water applied is attained at approximately 40 percent adequacy. Above about 70 percent adequacy dY/dX is less than 1.00 declining to zero at full moisture adequacy. These relationships are shown graphically in Figure 4.

By changing Y to a scale representing value of the production and X to cost of water the dY/dX curve then becomes an economic model. If an increased irrigation is not required for the maintenance of a favorable salt balance, it is logical to consider how far dY/dX should be permitted to decline before additional application of water becomes uneconomical.

Equation 15 is believed to be a good generalized representation of the moisture-yield function. However, the yield data from Cache Valley, Utah, do not fit Equation 15 very well. Five crops studied indicate a relationship that can be written:

$$Y = 2X - X^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (17)$$

indicating higher yields with lower moisture availability than is the case for the other data. Some technicians have attributed this to lateral soil water movement. Another possible explanation could be an underestimation of initial available moisture stored in the soil and of the effective rooting depths.

Equation 15 appears to be a good generalized relationship providing moisture deficiencies are not severe during critical periods. It should be further tested using yield data from a wider range of crops and conditions. Evaluation can be facilitated providing accurate measurements are made of total moisture available from all sources during the various growth stages of the crop.

MOISTURE DEFICIT CLASSIFICATION

Moisture deficits and adequacies depend upon amount and distribution of moisture and upon soil conditions. Based upon the data from Iran, Mirnezami (15), there is considerable doubt concerning the economic feasibility of dry farmed wheat production where the annual MAI is less than about 0.33. A higher index would be required in areas of shallow soils with little capacity to retain winter rains as available soil moisture. A composite index based upon both soils and climate might be developed. However, due to the complexity of soils in many areas such a combined index might be difficult to use.

Available yield data from California and Hawaii indicate that maximum yields are possible when available moisture is equal to 1.00 to 1.25 times ETA (actual crop evapotranspiration) under conditions of supply and distribution adequate to meet the evapotranspirative demand. In general, monthly values of MAI of 1.00 or somewhat more indicate an adequate supply of moisture from precipitation. However, for some soils and for some crops rainfall distribution may be less than adequate.

It would seem desirable to develop some form of standard classification for measuring moisture adequacies or deficits from the climatic conditions as the necessity arises. Hargreaves (11) proposed that MAI be adopted as a standard index for measuring water deficiencies and excesses, and that the following classification be used:

MAI = 0.00 to 0.33	very deficient
MAI = 0.34 to 0.67	moderately deficient
MAI = 0.68 to 1.00	somewhat deficient
MAI = 1.01 to 1.33	adequate
MAI = 1.34 and above	excessive.

This classification seems applicable for the more favorable soil conditions and is proposed for general usage. Where the soil moisture storage capacity is adequate for less than one week, the correlation between MAI and crop production probably will be lowered. The minimum values for economic production can then be expected to be correspondingly higher.

In a study of precipitation as related to agricultural production in Northeast Brazil, Hargreaves (9) used the following classification of climate.

Criteria	Climate Classification	Productivity Classification
All months with MAI in the range of 0.00 to 0.33	Very arid	Not suited for rainfed agriculture
One or two months with MAI of 0.34 or above	Arid	Limited suitability for rainfed agriculture
Three or four months with MAI of 0.34 or above	Semi-arid	Production possible for crops requiring a 3 to 4 month growing season
Five or more consecutive months with MAI of 0.34 or above	Wet-dry	Production possible for crops requiring a good level of moisture adequacy during 5 or more months.

In workshops in Brazil and in Mexico good agreement was found between this classification and agricultural potential. However, it appeared desirable to develop additional refinement particularly in the semi-arid classification.

The above criteria has been rapidly applied by computer in the analysis of climate and in evaluating range and agricultural potential for several countries in Latin America and Africa. Data are available for estimating ETP (Equation 4) and dependable precipitation, PD, from Equation 14 and modifications. Three references are required. These are Wernstedt (20) for precipitation and temperature; Lof, Duffie and Smith (14) for incident solar radiation; and World Meteorological Organization (22) for precipitation probabilities.

ACKNOWLEDGMENTS

The work presented herein was financed in part by the Agency for International Development through its contract AID/ta-c-1103 with Utah State University. The section on Leaching Requirements was rewritten from material furnished by Professor Emeritus J. E. Christiansen. Many of the concepts and definitions were developed jointly with Professor Christiansen. Useful suggestions and assistance with editing were provided by Professors Lyman S. Willardson and Byron C. Palmer. The views presented herein are those of the author and do not necessarily represent those of the Agency for International Development or Utah State University.

Table 1. Mean Daily Maximum Duration of Bright Sunshine Hours for Different Months and Latitudes.

Northern Lats / Southern Lats.	Jan. / July	Feb. / Aug.	March / Sept.	April / Oct.	May / Nov.	June / Dec.	July / Jan.	Aug. / Feb.	Sept. / Mar.	Oct. / Apr.	Nov. / May	Dec. / June
50°	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48°	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46°	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44°	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42°	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.9	11.1	9.8	9.1
40°	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35°	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30°	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25°	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20°	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15°	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10°	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5°	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0°	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1

Source: FAO Irrigation and Drainage Paper 24 (6).

Table 2. Extraterrestrial Radiation, RMD, Expressed in Equivalent Evaporation in mm/day.

Northern Hemisphere

Lat	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
50°	3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2
48	4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7
46	4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3
44	5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7
42	5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2
40	6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7
38	6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1
36	7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6
34	7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2
32	8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8
30	8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9.5	8.3
28	9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8
26	9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3
24	10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7
22	10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2
20	11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7
18	11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1
16	12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6
14	12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0
12	12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5
10	13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9
8	13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3
6	13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7
4	14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1
2	14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4
0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Southern Hemisphere

Lat	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
50°	17.5	14.7	10.9	7.0	4.2	3.1	3.5	5.5	8.9	12.9	16.5	18.2
48	17.6	14.9	11.2	7.5	4.7	3.5	4.0	6.0	9.3	13.2	16.6	18.2
46	17.7	15.1	11.5	7.9	5.2	4.0	4.4	6.5	9.7	13.4	16.7	18.3
44	17.8	15.3	11.9	8.4	5.7	4.4	4.9	6.9	10.2	13.7	16.7	18.3
42	17.8	15.5	12.2	8.8	6.1	4.9	5.4	7.4	10.6	14.0	16.8	18.3
40	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Source: FAO Irrigation and Drainage Paper 24(6)

Table 3. Crop Coefficients, KC, at Various Growth Stages

Crop	Planting to Effective Cover in Percent									
	10	20	30	40	50	60	70	80	90	100
Small Grains	0.19	0.22	0.30	0.44	0.61	0.80	0.98	1.13	1.23	1.25
Beans	0.24	0.28	0.36	0.47	0.61	0.76	0.91	1.05	1.18	1.28
Peas	0.24	0.29	0.37	0.48	0.61	0.76	0.90	1.04	1.16	1.26
Potatoes	0.12	0.16	0.24	0.36	0.49	0.64	0.78	0.91	1.02	1.09
Sugar beets	0.12	0.16	0.24	0.36	0.49	0.64	0.78	0.91	1.02	1.09
Corn	0.24	0.28	0.35	0.46	0.59	0.73	0.86	0.98	1.09	1.15
Alfalfa	0.43	0.56	0.70	0.82	0.94	1.08	1.20	1.20	1.20	1.20
Pasture	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
	Days After Effective Cover									
	10	20	30	40	50	60	70	80	90	100
Small Grains	1.25	1.13	0.89	0.59	0.23	0.12	0.12	0.12	0.12	0.12
Beans	1.22	1.15	1.02	0.88	0.71	0.54	0.37	0.23	0.12	0.12
Peas	1.18	1.22	1.19	0.91	0.24	0.12	0.12	0.12	0.12	0.12
Potatoes	1.08	1.02	0.90	0.72	0.46	0.12	0.12	0.12	0.12	0.12
Sugar beets	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
Corn	1.18	1.18	1.12	0.98	0.82	0.65	0.48	0.34	0.24	0.20
Alfalfa	0.90	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Pasture	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05

Source: ASCE Committee on Irrigation Water Requirements (1).

Table 4. Generalized Crop Coefficients, KC, for Estimating ETA.

Crop	* Average KC for Full Crop Cover	** Average Seasonal KC
Field and oil crops including beans, castor beans, corn, cotton, flax, peanuts, potatoes, safflower, soybeans, sorghum, sugar beets, tomatoes and wheat	1.15	.90
Fruits, nuts and grapes		
Citrus fruits (oranges, lemons and grapefruits)	.75	.75
Deciduous fruits (peaches, plums and walnuts	.90	.70
Deciduous fruits with cover crop	1.25	1.00
Grapes	.75	.60
Hay, forage and cover crops		
Alfalfa	1.35	1.00
Short grass	1.00	1.00
Clover pasture	1.15	
Green manure	1.10	.95
Sugar cane	1.25	1.00
Summer vegetables	1.15	.85

* Recommended for designing system capacity

** To be used in estimating seasonal requirements and for economic analysis. Provides satisfactory results for irrigation scheduling for most soils with good capacity to store readily available moisture.

Source: ASAE Transactions, Vol. 17, No. 4. 1974 (8).

Table 5. Approximate Range of Seasonal ET (crop) in mm and in Comparison with ET (grass).

ET (crop) seasonal	mm	%		mm	%
Alfalfa	600 - 1 500	90 - 105	Onions	350 - 600	25 - 40
Avocado	650 - 1 000	65 - 75	Orange	600 - 950	60 - 75
Bananas	700 - 1 700	90 - 105	Potatoes	350 - 625	25 - 40
Beans	250 - 400	20 - 25	Rice	500 - 800	45 - 65
Cocoa	800 - 1 200	95 - 110	Sisal	550 - 800	65 - 75
Coffee	800 - 1 200	95 - 110	Sorghum	300 - 650	30 - 45
Cotton	550 - 950	50 - 65	Soybeans	450 - 825	30 - 45
Dates	900 - 1 300	85 - 110	Sugarbeets	450 - 850	50 - 65
Deciduous			Sugarcane	1 000 - 1 500	105 - 120
trees	700 - 1 050	60 - 70	Sweet potatoes	400 - 675	30 - 45
Flax	450 - 900	55 - 70	Tobacco	300 - 500	30 - 35
Grains (small)	300 - 450	25 - 30	Tomatoes	300 - 600	30 - 45
Grapefruit	650 - 1 000	70 - 85	Vegetables	250 - 500	15 - 30
Maize	400 - 700	30 - 45	Vineyards	450 - 900	30 - 55
Oil seeds	300 - 600	25 - 40	Walnuts	700 - 1 000	65 - 75

Percentage values are based upon grass with a 12-month growing season as 100.
Source: FAO I&D Paper No. 24. (6)

Table 6. Crop Coefficient, KC, for Field and Vegetable Crops

Crop	Mid-Season	At Harvest
Barley	1.15	0.20
Beans (dry)	1.15	0.25
Carrots	1.10	0.80
Castor beans	1.15	0.50
Corn (maize)	1.15	0.60
Cotton	1.20	0.65
Crucifers (cabbage, cauliflower,etc)	1.05	0.90
Egg plant (anbergine)	1.05	0.85
Flax	1.10	0.20
Lettuce	1.00	0.90
Melons	1.00	0.75
Millet	1.10	0.75
Oats	1.15	0.20
Onions (dry)	1.05	0.80
Peanuts (groundnuts)	1.05	0.60
Peas	1.15	1.10
Peppers (fresh)	1.05	0.85
Potato	1.15	0.75
Radishes	0.85	0.80
Safflower	1.15	0.20
Sorghum	1.10	0.55
Soybeans	1.10	0.45
Spinach	1.00	0.95
Squash	0.95	0.75
Sugar beet	1.15	0.60-1.00
Sunflower	1.15	0.35
Tomato	1.20	0.65
Wheat	1.15	0.20

Source: FAO I&D Paper No. 24 (6).

Table 7. **Effective Plant Feeder Root Depths, and Recommended Amount of Available Moisture Depletion Before Irrigation is Begun.**

Crop	Depth in meters	Irrigation necessary when the following percent of available moisture has been used.
Alfalfa	1.20-1.80	50%
Beans	0.60	30%
Beets	0.60-0.90	40-50%
Cabbage	0.60	30%
Carrots	0.45-0.60	35-50%
Corn	0.60-1.20	30%
Cotton	0.90-1.20	50%
Cucumbers	0.45-0.60	30%
Grain (including sorghum)	0.60-0.75	50%
Grapes	0.90-1.50	50%
Lettuce	0.30	30%
Melons	0.60-0.75	30%
Onions	0.30-0.45	30%
Orchard	0.90-1.80	50%
Pasture	0.45-0.75	50%
Peanuts	0.45	30-35%
Peas	0.60-0.75	30-35%
Potatoes	0.60	30-35%
Soybeans	0.60	30-40%
Strawberries	0.30-0.45	30%
Sweet potatoes	0.75-0.90	30%
Tobacco	0.75	50%
Tomatoes	0.30-0.60	30-40%

Source: Griffin and Hargreaves (7)

Table 8. Critical Periods for Soil Water Stress for Different Crops.

Alfalfa	just after cutting for hay and at the start of flowering for seed production
Apricots	period of flower and bud development
Barley	early boot stage > soft dough stage > onset of tillering or ripening stage
Beans	flowering and pod setting period > earlier > ripening period. However ripening period > earlier if not prior water stress.
Broccoli	during head formation and enlargement
Cabbage	during head formation and enlargement
Castor bean	requires relatively high soil water level during full growing period
Cauliflower	requires frequent irrigation from planting to harvesting
Cherries	period of rapid growth of fruit prior to maturing
Citrus	flowering and fruit setting stages; heavy flowering may be induced by withholding irrigation just before flowering stage (lemon); ''June drop'' of weaker fruits may be controlled by high soil water levels
Cotton	flowering and boll formation > early stages of growth > after boll formation
Groundnuts	flowering and seed development stages > between germination and flowering and end of growing season
Lettuce	requires wet soil particularly before harvest
Maize	pollination period from tasselling to blister kernel stages > prior to tasselling > grain filling periods; pollination period very critical if no prior water stress
Oats	beginning of ear emergence possibly up to heading
Olives	just before flowering and during fruit enlargement
Peaches	period of rapid fruit growth prior to maturity
Peas	at start of flowering and when pods are swelling
Potatoes	high soil water levels; after formation of tubers, blossom to harvest
Radish	during period of root enlargement
Sunflower	possibly during seeding and flowering - seed development stage
Small grains	boot to heading stage
Sorghum	secondary rooting and tillering to boot stage > heading, flowering and grain formation > grain filling period
Soybeans	flowering and fruiting stage and possibly period of maximum vegetative growth
Strawberries	fruit development to ripening
Sugarbeet	3 to 4 weeks after emergence
Sugarcane	period of maximum vegetative growth
Tobacco	knee high to blossoming
Tomatoes	when flowers are formed and fruits are rapidly enlarging
Turnips	when size of edible root increases rapidly up to harvesting
Water melon	blossom to harvesting
Wheat	possibly during booting and heading and two weeks before pollination.

Source: FAO I&D Paper No. 24.(6)

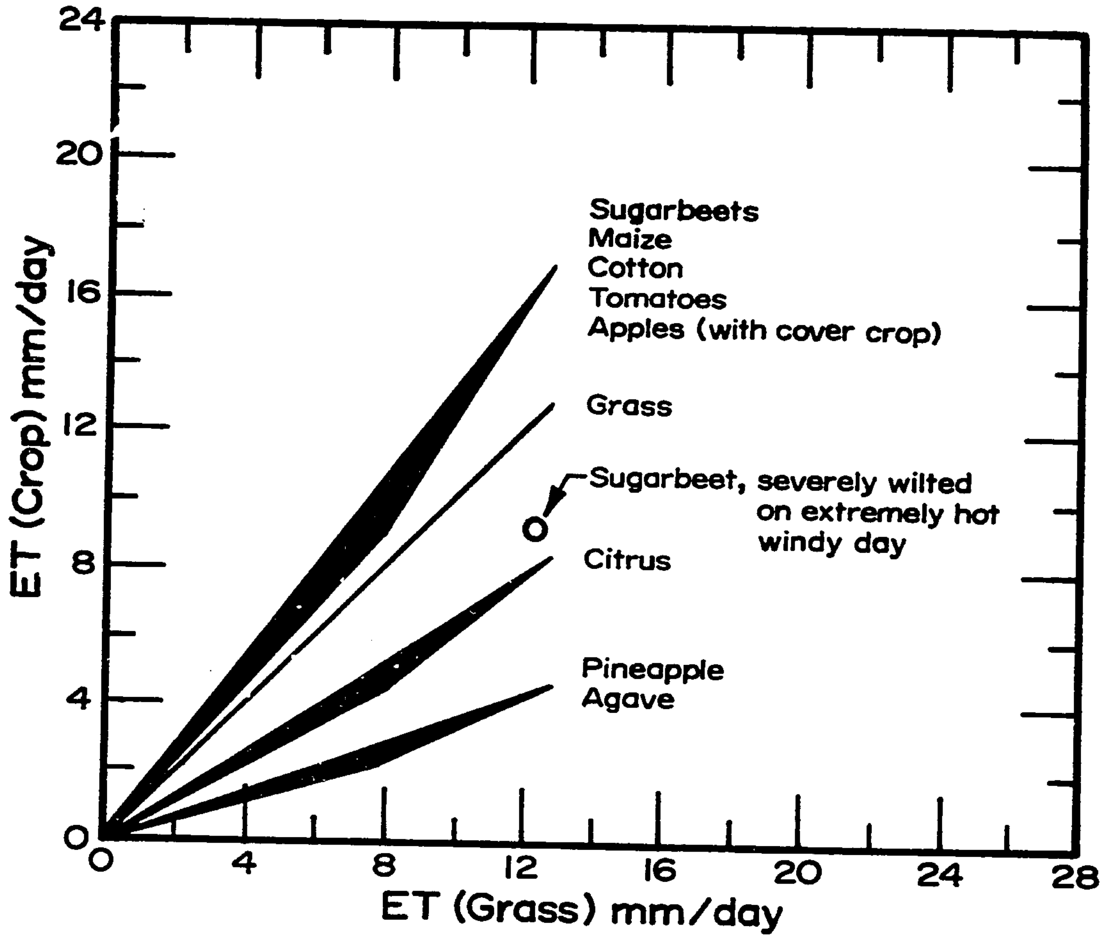

Figure 1. Magnitudes of ET (Crop) as Compared to ET (Grass).
Source: FAO I&D Paper No. 24.

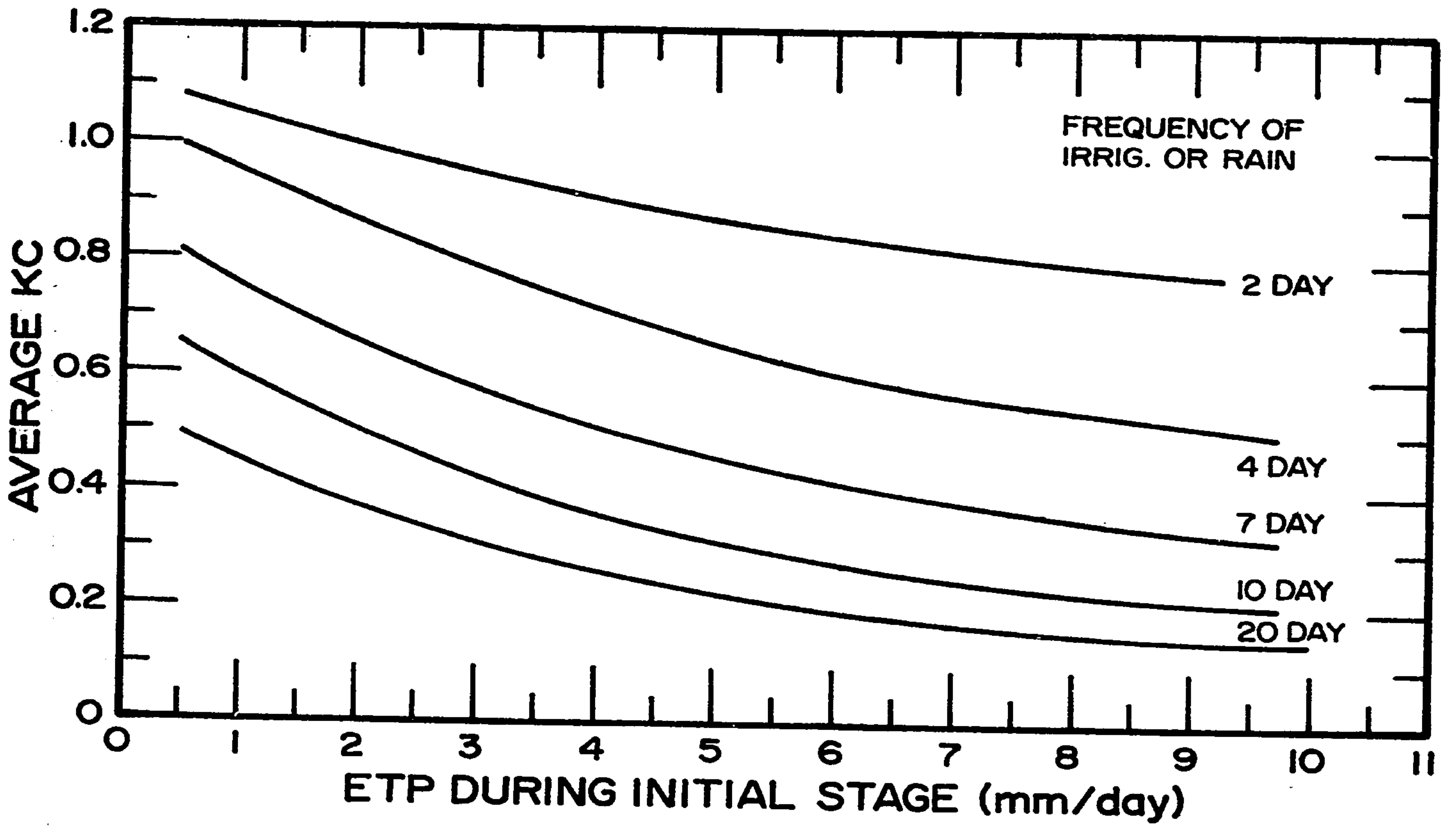

Figure 2. Average KC for Initial Stage as a Function of Average ETP Level (during initial stage) and Frequency of Irrigation or of Significant Rain.

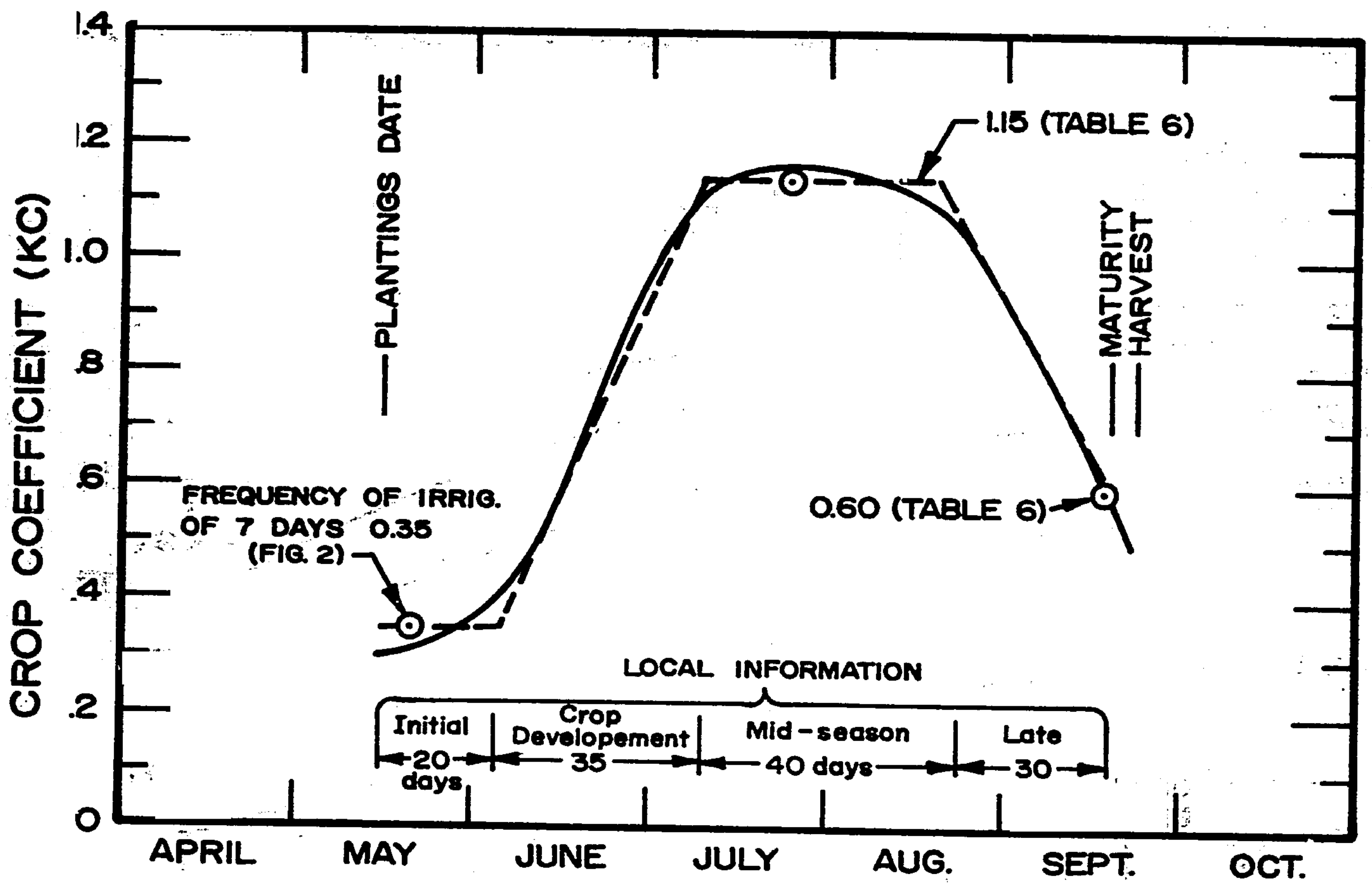

Figure 3. Example of Crop Coefficient Curve (for corn).

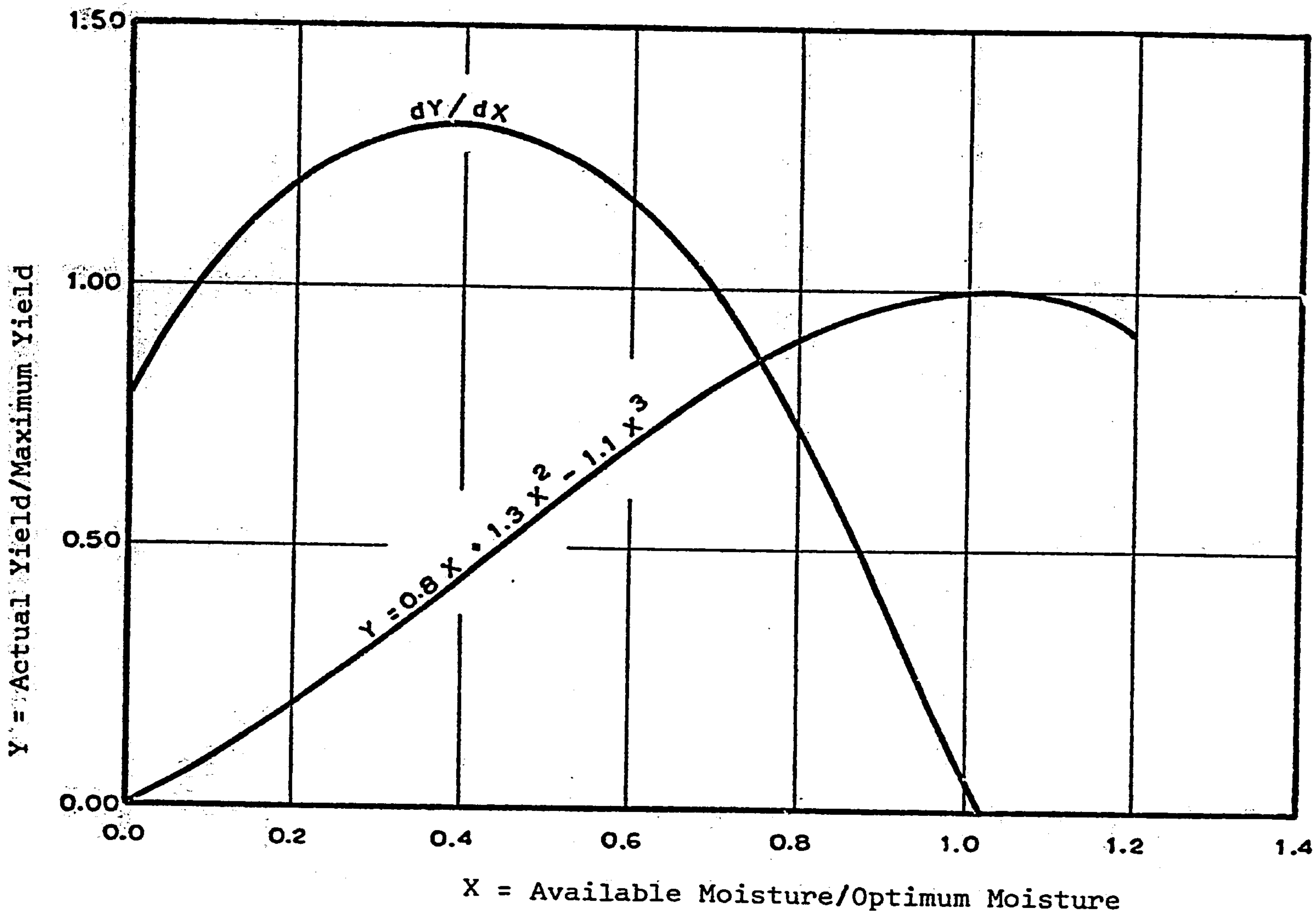

Figure 4. Moisture Adequacy and Yield Function.

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APPENDIX II - COMPUTER EQUATIONS

```
      REAL MAI
      DIMENSION NAME(6),DEC(12),ES(12),DM (12),Z(12),OM(12),DL(12),RLD(12
     1?,TM(13),TF(13),RHM(12),RS(13),S(13),HM(13),ETPH(13),ETPS(13),ETPR
     2S(13),PM(13),L(12),RSM(13),RSMI(13),CH(12),PD(12),ETDF(12),MAI(12)
      DATA (DM(M), M=1,12)/31.,28.,31.,30.,31.,30.,31.,31.,30.,31.,30.,
     131./
C     DM IS NUMBER OF DAYS IN THE MONTH
      DATA (DEC(M),M=1,12)/-.3656,-.2365,-.04682,.1607,.3247,.4017,
     $.3699,.2360,.03995,-.1669,-.3291,-.4021/
C     DEC IS DECLINATION IN RADIANS
      DATA (ES(M),M=1,12)/.97104,.98136,.99653,1.01313,1.02625,1.03241,1
     $.02987,1.01916,1.00347,.98693,.97369,.96812/
C     ES IS MEAN MONTHLY DISTANCE OF THE SUN TO THE EARTH DIVIDED BY THE
C     MEAN ANUAL DISTANCE
      JJ=0
C     NAME IS STATION AND COUNTRY
C     NYRS IS NUMBER OF YEARS OF RECORD
C     NELEV IS ELEVATION IN METERS
C     LD IS LATITUDE IN DEGREES   LDM IS LATITUDE IN MINUTES
C     LO IS LONGITUDE IN DEGREES    LOM IS LONGITUDE IN MINUTES
    2 READ(5,100,END=261) NAME,NYRS,NELEV,LD,LDM,LO,LOM
  100 FORMAT(6A6,I4,I5,5X,I2,I3,2X,I3,I3)
C     TM IS MEAN TEMPERATURE IN DEGREES CENTIGRADE
      READ(5,120)(TM(M),M=1,12)
C     PM IS MEAN PRECIPITATION IN MM
  120 FORMAT(5X,12F5.1)
      READ(5,120)(PM(M),M=1,12)
C     RS IS INCIDENT SOLAR RADIATION IN LANGLEYS PER DAY
      READ(5,122)(RS(M),M=1,12)
C     S IS MEAN PERCENTAGE OF POSSIBLE SUNSHINE
  122 FORMAT(5X,12F5.0)
      READ(5,122)(S(M),M=1,12)
C     HM IS MEAN RELATIVE HUMIDITY IN PERCENT
      READ(5,122)(HM(M),M=1,12)
      JJ=JJ+1
      XLA=(FLOAT(LD)+FLOAT(LDM)/60.)
C     XLA IS LATITUDE IN DEGREES AND DECIMALS
      XLR=(FLOAT(LD)+FLOAT(LDM)/60.)/57.2958
C     XLR IS LATITUDE IN RADIANS
  205 FORMAT (1H0/)
      IF(MOD(JJ,3).EQ.1) WRITE(6,205)
  102 FORMAT(1H1,'TABLE 1  CLIMATE AND POTENTIAL EVAPOTRANSPIRATION FOR
     1NAME OF COUNTRY        ')
      IF(MOD(JJ,3).EQ.1) WRITE(6,102)
C     MOD STATEMENTS PRINT THREE STATIONS PER PAGE
      IF(MOD(JJ,3).EQ.1) WRITE(6,203)
      PRINT 101,NAME,NYRS,NELEV,LD,LDM,LO,LOM
  101 FORMAT(' ' /     ,6A6,'    YRS',I3,'  ELEV',I5,'  LAT',I4,I3,'  LON'
     1,I4,I3,/
     2 '0          JAN   FEB   MAR   APR   MAY   JUN   JUL   AUG   SEP
     3  OCT   NOV   DEC  SUM OR AV.     '/)
      TM(13)=0.
      PM(13)=0.
      RS(13)=0.
      S (13)=0.
      HM(13)=0.
      ETPH(13)=0.
      ETPS(13)=0.
      ETPRS(13)=0.
      DO 3 M=1,12
      Z(M)=-TAN(XLR)*TAN(DEC(M))
      OM(M)=ACOS(Z(M))
      DL(M)=OM(M)/.1309
C     DL IS DAY LENGTH IN HOURS (SUNRISE TO SUNSET)
      RLD(M)=916.732*(OM(M)*SIN(XLR)*SIN(DEC(M))+COS(XLR)*COS(DEC(M))*SI
     1N(OM(M)))/ES(M)
      TF(M)=32.+1.8*TM(M)
      RHM(M)=OM(M)*10.*RLD(M)/(595.9-.55*TM(M))
```

```
C     RMM IS EXTRATERRESTRIAL RADIATION IN MM PER MONTH
C     ETP IS POTENTIAL EVAPOTRANSPIRATION IN MM PER MONTH
      CLA=.17*SQRT(70.-ABS(XLA))
      IF(CLA.GT.1.00) CLA=1.00
      CH(M)=.166*(SQRT(100.-HM(M)))
      IF(CH(M).GT. 1.00)CH(M)=1.00
C     ETPH IS ETP CALCULATED FROM HUMIDITY TEMPERATURE AND LATITUDE
      ETPH(M)=.0000158*RMM(M)*DL(M)*TF(M)*CLA*CH(M)*25.4
C     L IS LATENT HEAT OF VAPORIZATION
      L(M)=595.9-.55*TM(M)
C     RSMI IS INCIDENT SOLAR RADIATION IN EQUIVALENT MM OF EVAPORATION
C     CALCULATED FROM RMM AND S
      RSMI(M)=.075*RMM(M)*SQRT(S(M))
C     ETPS IS ETP ESTIMATED FROM SUNSHINE PERCENTAGE AND TEMPERATURE
      ETPS(M)=.0075*RSMI(M)*TF(M)
C     RSM IS SOLAR RADIATION CONVERTED TO EQUIVALENT MM OF EVAPORATION
      RSM(M)=RS(M)*DM(M)*10./L(M)
C     ETPRS IS ETP ESTIMATED FROM SOLAR RADIATION AND TEMPERATURE
      ETPRS(M)=.0075*RSM(M)*TF(M)
      TM(13)=TM(13)+TM(M)
      PM(13)=PM(13)+PM(M)
      RS(13)=RS(13)+RS(M)
      S (13)=S (13)+S (M)
      HM(13)=HM(13)+HM(M)
      ETPH(13)=ETPH(13)+ETPH(M)
      ETPS(13)=ETPS(13)+ETPS(M)
      ETPRS(13)=ETPRS(13)+ETPRS(M)
C     PD IS THE DEPENDABLE PRECIPITATION AT 75 PERCENT PROBABILITY
      PD(M)=-23.+.84*PM(M)
      IF(PD(M).LT. 0.01) PD(M)=0.
C     THE EQUATION FOR PD IS DETERMINED FOR EACH CLIMATIC ZONE OR
C     COUNTRY. THE ABOVE EQUATION IS FOR THE 13 SOUTHEASTERN U.S. STATES
C     ETDF IS EVAPOTRANSPIRATION DEFECIT
      ETDF(M)=ETPRS(M)-PD(M)
C     MAI IS THE MOISTURE AVAILABILITY INDEX
      MAI(M)=PD(M)/ETPRS(M)
    3 CONTINUE
      TM(13)=TM(13)/12.
      RS(13)=RS(13)/12.
      S (13)=S (13)/12.
      HM(13)=HM(13)/12.
      PRINT 107,(TM(M),M=1,13)
  107 FORMAT(' MEAN TEMP', 12F6.1,F8.1)
      PRINT 108,(PM(M),M=1,13)
  108 FORMAT(' MEAN PREC', 12F6.0,F8.0)
      PRINT 109,(RS(M),M=1,13)
  109 FORMAT(' MEAN RS   ', 12F6.0,F7.0)
      PRINT 110,(S (M),M=1,13)
  110 FORMAT(' MEAN S    ', 12F6.0,F7.0)
      PRINT 111,(HM(M),M=1,13)
  111 FORMAT(' MEAN HM   ', 12F6.0,F7.0)
      PRINT 112,(ETPH(M),M=1,13)
  112 FORMAT(' POT ET H ', 12F6.0,F8.0)
      PRINT 113,(ETPS(M),M=1,13)
  113 FORMAT(' POT ET S ', 12F6.0,F8.0)
      PRINT 114,(ETPRS(M),M=1,13)
  114 FORMAT(' POT ET RS', 12F6.0,F8.0)
      PRINT 115,(PD(M),M=1,12)
  115 FORMAT(' DEP PREC ', 12F6.0)
      PRINT 116,(ETDF(M),M=1,12)
  116 FORMAT(' ET DEF.  ', 12F6.0)
      PRINT 117,(MAI(M),M=1,12)
  117 FORMAT(' MAI      ', 12F6.2)
  203 FORMAT(1H ,'--------------------------------------------------------------
     1-----------------------------')
      WRITE(6,203)
      GO TO 2
  261 STOP
      END
```

END OF COMPILATION: NO DIAGNOSTICS.