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Crop Water Requirements and Agricultural Drought Assessment Manual

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CROP WATER REQUIREMENTS AND AGRICULTURAL DROUGHT ASSESSMENT MANUAL

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CROP WATER REQUIREMENTS AND AGRICULTURAL DROUGHT ASSESSMENT MANUAL

By George H. Hargreaves[1] and Zohrab A. Samani[2]

EXECUTIVE SUMMARY

Drought and disaster have been fairly common throughout recorded history. In several developing countries, population growth exceeds growth in agricultural production. Attempts to increase production or efforts for survival sometimes result in the degradation of the soil and water resources.

An agricultural drought is herein defined as a lack of moisture causing extensive loss of potential for agricultural production. Rainfall is cyclical and periods of better than normal or average conditions have sometimes lasted a decade or more. During these favorable cycles, population pressures may result in the use and development of lands that are not suitable for agriculture during adverse climatic cycles.

Historically, settlements have occurred on flood plains adjacent to rivers. These areas frequently comprise the best agricultural lands and those areas where irrigation is most feasible. By definition flood plains have the highest risk of damage and/or crops loss due to floods or waterlogging.

Drought and flood risk assessment consists of an evaluation of the probabilities of various degrees of water shortage or excess and the damages that may result therefrom. This manual is primarily concerned with the probable magnitude of water shortage and of excessive rainfall.

The executive or decision-maker within a developing nation must consider the political consequences of his decisions or policies. Attempts to provide more food production for increasing popula-

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tions may result in the degradation of the potential productivity of the soil and water resources.

This manual provides methods for estimating water requirements for irrigated and rainfed agriculture, the relationship between water adequacy and potential crop yields and guidance for evaluating the probable reoccurrence of floods, droughts and disasters.

The introduction briefly summarizes the contents. This executive summary attempts to present the concepts in simple terms with a minimum of technical considerations.

Terms commonly used and some new concepts are defined in order to provide clarity and standardization. Potential Evapotranspiration (PET) is referenced to a cool-season grass (Alta fescue grass). Dependable Precipitation (PD) is the 75% probability of assured rainfall. A Moisture Availability Index (MAI) is proposed as an indication of rainfall adequacy (MAI = PD/PET).

A comparison of more than a score of methods for estimating PET indicates that only measurements of maximum and minimum temperatures are required for accuracy, reliability, simplicity and universality of application (see equation 3). The equation can be further simplified for local use due to the linear relationship of temperature with elevation.

The amount of water available to the crop from rainfall or from irrigation should be compared with potential evapotranspiration (PET). Allowance should be made for the crop growth stage (Table 2). PET can be approximated for low elevation locations as about 0.36 times extraterrestrial radiation (Ra). Values of Ra for each month and latitude are given in Table 1. When the water requirement is fully supplied by rain, PET will be somewhat reduced due to the influence of rainfall on temperature. In this case PET will be about 0.30 times Ra. These coefficients of 0.36 and 0.30 can usually be decreased about 2.2% for each 100 m increase in elevation.

Several models have been developed to relate potential crop yield to water availability or to crop water use. The Stewart equation (equation 9) is one of the most widely used of those models.

Although there is much variability by different crops in their yield response to water, an average yield reduction is roughly proportional to the reduction in crop evapotranspiration (ETC). The average relationship is approximately the same percentage reduction in yield as the reduction in ETC. The available research information indicates that crop production is usually not economical when the water availability is at about one third adequacy or less. The economical use of fertilizers generally requires about 45% or more of full water adequacy. Where irrigation is practiced, application of less than full adequacy will frequently produce the maximum economical returns.

Good agricultural development or policy planning requires the availability of climatic data. Long-term records of daily rainfall are required. These should be accessable to those engaged in planning and research. Daily records of maximum and minimum temperatures are also required. However, due to the good relationship between elevation and temperature, measurements do not need to be made at nearly as many locations as required for rainfall.

Daily rainfall data can also be used for estimating extreme rainfall intensities and flood risk probabilities. Depth-duration-frequency rainfall amounts for durations of one half hour or more and for return periods (frequencies) of from 5 to 100 years can be estimated from a long record of daily rainfall amounts (see equation 11).

Graphical presentations of probabilities of occurrence as presented in Figure 2 assist in the prediction of drought and flood risks. However, monthly probabilities are less than adequate. Shorter time periods of 10 days or less are recommended.

This manual is mainly concerned with the use of historical data to predict risk. However, significant emphasis needs to be given to the use of real time data and production practices. The procedures presented need to be applied to crop monitoring and yield records. Some of the relationships need simplification. Greatly expanded use of the methodolcgy for zoning of countries and regions is recommended.

INTRODUCTION

The pressures on the developing nations to feed more people have frequently lead to a degradation of the potential productivity of soil and water resources in the rangelands and areas devoted to rainfed crop production. A large portion of the rainfed agricultural area consists of arid and semi-arid lands. A knowledge of the climate and of the other resources of a region can assist in developing policies that will determine whether the potential to support human life will decrease or be improved. Since both degradation and rehabilitation can at times be very rapid, it is urgent that policy makers develop a clear understanding of the factors relating to agricultural productivity.

Water availability is a dominant factor that determines variability in crop production from place to place and from year to year. This manual provides criteria for drought risk assessment. An agricultural drought is a lack of moisture or a period of dryness causing extensive damage to crops or a loss of potential to produce crops or useful vegetation. Risk assessment includes an evaluation of probabilities of occurrence and of severity. The concept of drought is often relative to some norm or requirement. Water requirements for range, sorghum, maize and rice are all different. The degree of risk depends upon the relationship of water availability to water requirements in each case. For range productivity, a normal year following several good years has sometimes been described as drought.

Frequently, the evaluation of the risks of flood damage to facilities and/or agricultural production are not adequately evaluated. Flood risk assessment involves determining the probable frequency of occurrence of extreme rainfall amounts and some form of evaluation of the probable damage or loss that may occur as a result of waterlogging, inundation or physical destruction by flood waters. The assessment described in the manual provides methodology for evaluating the probabilities of extreme rainfall amounts.

Assessment of risk is closely related to an evaluation of potential production or potential benefits. Crop water requirements can be reliably evaluated from temperature and temperature correlates well with elevation resulting in a minimum of data and computational requirements. Water availability is used in numerous crop yield models to make comparisons with water requirements and to predict the potential crop yields.

The principal terms used in this manual are defined in order to prevent misunderstanding and to make the material more useful for those who are not highly specialized in the subject matter presented. Various reference crops are used for developing emperical equations for potential evapotranspiration and crop coefficients consequently have not been well standardized. The definitions given clearly define the reference crop, the methodology and the concepts used in evaluating productivity and risk.

Numerous comparisons have been made of procedures for estimating potential evapotranspiration and crop water requirements. The results of several of these comparisons are described and a methodology is selected as superior to others based on the advantages of simplicity of computation, reliability of results and the lack of requirements for local calibration. The method selected requires only measurements of maximum and minimum temperatures.

Air temperatures decline with elevation. Crop water requirements can, therefore, after suitable evaluation of local conditions, be reliably estimated from latitude and elevation. Some modification of this procedure seems desirable to compensate for the reduction in temperature produced by rainfall.

The effects of drought may be eliminated or moderated by irrigation, providing the water supply is adequate. The optimization of the use of limited supplies of water is related to irrigation efficiencies and to the economics of deficit irrigation.

Risk assessment requires availability of the required data. The most important variable is rainfall. Daily values of maximum and minimum temperatures are desirable but daily rainfall records are essential. Monthly and ten day rainfall amounts are useful and provide for considerable evaluation of risks. However, good agro-climatological analyses require daily records.

Daily rainfall data are useful in evaluating the yield potential for crop, forage, and forest production. These data can also be used for estimating the probable depth-duration-frequency rainfall amounts for durations of from one half hour to several days and return periods of from 5 to 100 years.

Several probabilities of assured rainfall can be plotted and a graph prepared showing the range of probabilities compared with potential crop water requirements and one third of potential evapotranspiration. These graphs provide a good indication of the range of probabilities and the risks associated with low or extreme rainfall amounts.

Crop production needs to be monitored and compared with the results from models that input daily temperature and rainfall to predict potential yields. Additional techniques are needed that relate more directly to the famers understanding of agriculture. For example, in Mali the moisture availability index (MAI) can be estimated from the number of days of rain in the month. The equation predicts 92% of the variance. The farmer may not readily understand the MAI but can count days of rain and learn the significance relative to farming practices.

For several countries or regions, zoning has been developed based on the criteria presented herein (number of months with MAI above 0.33). The zoning has been used to establish agricultural credit policies, for land use and settlement, for designing agricultural research and for agricultural development planning and financing.

DEFINITION OF TERMS

In order to facilitate an understanding of crop water requirements for good growth and production it is desirable that various terms and symbols be clearly defined.

Evapotranspiration, ET, is the process by which water is transferred from the plant and soil into the atmosphere. It includes evaporation from plant and soil surface and transpiration of water through the plant tissue. The rate of ET is usually expressed as equivalent depth of water per unit time (e.g. mm/day or mm/month).

Potential Evapotranspiration, PET, is also referred to as ETP or as reference crop evapotranspiration, ETo. PET is the rate of ET from an extensive surface of 8 to 15 cm tall, green, cool-season (C3) grass cover of uniform height, actively growing, completely shading the ground and not short of water. The principal reference crops that produce comparable values of PET are the tall fescues and perennial ryegrass. Kentucky bluegrass may also be used as an index or reference crop. The warm season grasses usually have lower rates of ET than the cool season grasses. The ratios of these rates vary significantly with temperature. The basic equations used herein were derived form the ET rate of Alta fescue grass (one of the tall fescues) grown in 29 m^2 lysimeters at Davis, California.

Potential Crop ET, ETC, is the potential ET of agricultural crops grown under disease-free conditions in large fields under non-restricting soil conditions including water and fertility and achieving full production potential. The crops should be grown under favorable temperature and other climatic conditions for good levels of commercial production. ETC may be measured under field conditions or estimated by multiplying PET times the appropriate crop coefficients, Kc, for the various stages of crop growth. ETC is equivalent to ET (crop) as used by Doorenbos and Pruitt, 1977.

Extraterrestrial Radiation, Ra, is the amount of radiation received at the top of the atmosphere. Ra may be measured in various energy units. The amount of energy required to evaporate water varies somewhat with temperature, but this variation is quite small within the range of suitable temperatures for crop growth. For that reason, Ra is often expressed in equivalent mm of water evaporation. Ra is dependent only on latitude and the time of the year. Various computer equations have been developed for calculating Ra and Doorenbos and Pruitt, 1977, have provided a convenient table of monthly values of Ra for latitudes 0 to 50 degrees in equivalent mm of water evaporation per day.

Solar Radiation, Rs, is that portion of Ra reaching the earth's surface. Part of Ra is absorbed and scattered when passing through the atmosphere. Of 18 methods for estimating PET compared by Jensen, 1974, the majority use either Rs or net solar radiation. More recently, a method has been found for estimating Rs from the range between maximum and minimum temperatures and Ra. This procedure improves PET estimates and eliminates the need for either measured or calculated values of Rs.

Dependable Precipitation, PD, is assured rainfall at a pre-determined probability level. The 75 percent probability has been widely used and is proposed as an index of dependable amounts of rainfall for crop production. Effective rainfall is that portion that becomes available for use by the crops. The portion that becomes effective depends upon potential crop use, the soil conditions, rainfall frequency, distribution and intensities and to land preparation and various cropping and management practices. Because of the number of factors that influence the amount of effective rainfall, the use of equations or tables for its estimation can be very misleading. It is proposed that PD be used as an indication of the dependable rainfall amount and that management practices be developed to maximize or optimize the benefits from the available rainfall.

Moisture-Availability Index, MAI, is a relative measure of the precipitation available for supplying moisture requirements. It is computed by dividing PD by PET (MAI = PD/PET). MAI is proposed as an index of the portion of the potential crop water requirements that can be made available under suitable management from rainfall. It provides an index of the probable effective length of the growing season for rainfed agriculture. Some regions and countries have been zoned by mapping areas of equal numbers of months with MAI values above a predetermined value. MAI exceeding 0.33 has frequently been used as a mapping criteria.

Crop Coefficient, Kc is the crop ET (ETC) divided by PET. Kc accounts for the crop characteristics, the stage of growth and degree of ground cover as well as other factors that influence the crop evapotranspiration. Tables of values of Kc have been developed by comparing measured ETC with values of PET for corresponding stages in crop growth. Doorenbos and Pruitt, 1977, and Doorenbos and Kassam, 1979, present crop coefficients that correspond with PET from a cool season grass reference crop. These values of Kc should not be used with evapotranspiration of alfalfa or with that of warm season reference crops as an index of potential water use. The Kc values referenced above are associated with high yields and the current better agricultural practices. The values given by Doorenbos and Pruitt, 1977, and Doorenbos and Kassam, 1979, have been confirmed by comparison with measured ETC and estimated values of PET under the more productive cropping practices in California.

COMPARISONS OF PET ESTIMATING METHODS

More than a score of methods have received significant use of estimating PET. Numerous comparisons of methods have been made. Many of these comparisons are inconclusive. This results from a wide range of factors including:

1. Use of reference crops with differing water use requirements.
2. Use of a temperature range that is not well suited to the requirements of the reference crop.
3. Differences in water requirements of various varieties of the same crop. Cold tolerant alfalfas have differing water requirements from other varieties.
4. Lack of standardization of the guard area around a lysimeter.
5. Differences in clipped height, frequency of watering, of soil depth and fertility, differences in the type of lysimeter used, etc.

Jensen, 1974, compared 18 methods for estimating PET using lysimeter data from 10 locations. At one location, the reference crop was a warm season grass. At two locations, different varieties of alfalfa were used and at 7 sites the reference can be considered to be cool season grasses or grass mixtures with clover, etc. For coastal locations, the best three methods evaluated based upon the lowest root mean square, RMS, difference between measured and calculated values were Christiansen Rs, Turc, and Kohler, et al. For the inland semi-arid to arid locations, the three best were Jensen-Haise, Van Bavel-Businger 0.25 and Penman.

Jensen, 1974, presents graphs comparing PET from each of the 18 methods with measured lysimeter ET. Climatic data are given for three months at each location (May, July, and September for N. Lat. and November, January, and March for S. Lat.). Hargreaves, 1975, developed an equation that estimates PET as proportional to the product of solar radiation, Rs, and Fahrenheit temperature or to Rs times temperature in °C plus 17.8. When compared with enlargements of Jensen's graphs, the Hargreaves Rs method appears superior to the others for most inland locations. For mountainous, high elevation and highly advective locations, this method underestimates PET and for the coastal locations overestimates PET. However, the differences are such that the equation is not considered inferior to any of the 18 methods evaluated by Jensen.

McVicker, 1982, calibrated 12 methods by using Alta fescue grass ET from the lysimeters at Davis, California. The equations were then evaluated using data from two locations. They were ranked in order of lowest RMS differences as follows: Hargreaves, Jensen-Haise, Stephens and Stewart, Makkink, Turc, Grassi, Modified Penman, etc. The first six with the smaller RMS errors are all based upon RS and mean air temperature. After calibration they did not vary significantly in performance. McVicker found that addition of wind run, dew-point temperature and estimated net radiation increased model complexity but decreased predictive accuracy.

Salih and Sendil, 1984, compared alfalfa ET in an extremely arid climate at two locations in Saudi Arabia with estimated PET from several methods. Those methods based on Rs and temperature and the Class A pan method ranked highest.

Hargreaves and Samani, 1982, compared PET calculated from four methods with measured lysimeter ET from eight locations in California and one in Australia. The California data are for cool season grasses. In Australia the comparisons are with both ryegrass and kikuyu grass. Of the four methods evaluated, the product of temperature in degrees Fahrenheit times Rs and the Class A pan sited in a large irrigated pasture produced the highest coefficients of determination and the lowest standard deviations of ratios of measured lysimeter ET divided by calculated PET.

Shih, 1984, analyzed the relationship between ET and various climatic measurements and concluded that in estimating ET one should limit the climatological data to temperature and Rs.

Hargreaves and Samani, 1983, and Hargreaves, 1984, compared lysimeter ET from Damien in Haiti with PET estimates from several equations including the FAO Penman and other equations given by Doorenbos and Pruitt, 1977. The product of temperature times Rs outperformed the other equations evaluated. The equation developed by Hargreaves, 1975, is:

$$PET = 0.0075 \times Rs \times T°F \qquad (1)$$

in which PET and Rs are in the same units and T°F is mean air temperature in degrees Fahrenheit.

Equation 1 has received considerable acceptance for irrigation planning and design, for irrigation scheduling and for evaluating the potential for rainfed agricultural production. Hargreaves and Samani, 1982, and others have attempted to correct for the difference between measured and estimated values by adding coefficients for wind, relative humidity, or other factors. Unfortunately, these attempts did not produce significant improvement of the basic equation.

One weakness of Equation 1 is the scarcity of reliable measurements of Rs. Hargreaves (cited by Hargreaves and Samani, 1982) derived an equation for Rs from the difference between mean maximum and mean minimum temperatures, TD, and extraterrestrial radiation, Ra. The equation is:

$$Rs = K_t \times Ra \times TD^{0.50} \qquad (2)$$

in which Rs and Ra are in the same units and K_t is a coefficient that requires some calibration.

Measured and estimated values of Rs were used to calibrate K_t for Africa, India, Brazil and the United States. The values of K_t are higher near the ocean due to the moderating effect on the temperature range, are approximately the same world-wide for plains, plateaus and large valleys and tend to be lower in high mountain valleys and in conditions where the temperature range is increased due to movements of colder air down the mountains. These differences in K_t approximately compensate for the differences between lysimeter ET and PET estimated from equation 1.

A UNIVERSAL EQUATION FOR PET

The above literature review indicates that equation 1 is probably superior to the other methods evaluated for interior locations of fairly plain topography. Under these conditions K_t appears to be uniform worldwide, at least for the frost-free growing season for most crops. Combining equations 1 and 2 and calibrating using the Alta fescue grass lysimeter ET from Davis, California and the available solar radiation data for India, Africa, Brazil and the United States results in the equation:

$$PET = 0.0023 \times Ra \times (T°C + 17.8) \times TD^{0.50} \qquad (3)$$

in which PET and Ra are in the same units. Values of Ra in mm per day from Doorenbos and Pruitt, 1977 are given in Table 1. Equations for calculating Ra are presented in Appendix 2.

Table 1. Extra Terrestrial Radiation (Ra) Expressed in Equivalent Evaporation in mm/day.

Northern Hemisphere													Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Lat	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2	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
4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7	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
4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3	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
5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7	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
5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2	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
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	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
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	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
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	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
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	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
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	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
8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9.5	8.3	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
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	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
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	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
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	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
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	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
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	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
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	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
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	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
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	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
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	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
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	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
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	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
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	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
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	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
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	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
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	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: Doorenbos and Pruitt, 1977

Equation 3 has been evaluated by comparison with cool season grass lysimeter ET at several locations. In each case the estimated values of PET from equation 3 were as close or closer to the lysimeter ET than the PET values obtained using equation 1. For coastal and highly advective conditions equation 3 is significantly better than equation 1.

Equation 3 can also be written:

$$PET = 0.00094 \times Ra \times T°F \times TD^{0.50} \qquad (4)$$

In both equations 3 and 4, TD is in the same temperature units as the mean air temperature.

Equations 3 and 4 are recommended for general worldwide use without calibration. From the comparisons of PET estimating methods presented above it seems apparent that the addition of corrections or other factors would increase complexity without contributing to accuracy.

Measurements of radiation, Rs, may have significant error. Instrument calibrations frequently drift. Hargreaves and Samani, 1982, report that one of the California instruments produced measurements of Rs that were 10 to 12 percent too low. Rs is frequently calculated from measured sunshine hours. Temperature is usually measured with greater accuracy than most other climatic measurements. Doorenbos, 1976, gives the expected errors as follows:

Observation	Instrument Error	Exposure Error	Observer Error	WMO Standard
Temperature	0.5°C	2° C	0.5°C	0.1°C
Sunshine	5-10%	10%	10%	10%
Rainfall	2-5%	10%	5%	2%

Equations 3 and 4 have the following advantages over most other methods for estimating PET:

1. There is less need for local calibration.
2. The difference between measured and estimated values are usually less.

3. The data requirements are minimal and the errors in the data are usually lower.
4. The computation is very simple, easily understood and readily programmed by calculator or computer.

ESTIMATING PET WITHOUT DATA

The mean air temperature usually declines about 5.5 to 6.0° C per 1000 meter increase in elevation. If temperature data are not available, PET can usually be estimated with reasonable accuracy by using data from a location of similar elevation, latitude and rainfall amounts. For a narrow range of latitude, say about 2°, equations can usually be developed from the available temperature measurements for each month. A regression can be made to develop equations that relate temperature with elevation (El) as follows:

$$T_{mx1} = a_1 + b_1 \times El \qquad (5)$$

and

$$T_{mi1} = c_1 + d_1 \times El \qquad (6)$$

in which T_{mx1} and T_{mi1} are the maximum and minimum temperatures for the first month, January. T_{mx2} and T_{mi2} are the maximum and minimum values for February. In this manner, equations for temperature can be developed for each month from the available data. The coefficient of determination for these computer equations is usually quite high. These regressions may be accomplished on a small programable calculator or, if preferable, the equations may be obtained by plotting a graph of the available data. For a large number of calculations, computer facilities may be preferred.

After estimating the mean temperature and the value of TD, PET can be calculated by using equation 3 with the appropriate value of Ra from Table 1.

For various locations, the calculation of PET can be further simplified. For El Salvador there is little variation in latitude and both maximum and minimum temperatures are highly correlated with elevation. PET decreases 2.2% per 100 mm increase in elevation. By using this relationship, reasonable estimates of PET for the entire country require measurement of temperature at only a few locations.

An analysis of weekly climatic data from one location in the Mahaweli Project in Sri Lanka resulted in the equation:

$$PET = KR \times Ra \tag{7}$$

in which KR is a coefficient that varies somewhat with rainfall. For this location, KR was 0.36 for those weeks without rain, 0.33 for weeks with rain of less than 50 mm and 0.29 for a week with 50 mm or more of rain. The results from equation 7 are close enough to those from equation 3 so that equation 7 is quite satisfactory for irrigation scheduling and for evaluating the potential for rainfed agriculture. This analysis was made in a non-irrigated area. In an irrigated area at considerable distance, but also within the Mahaweli Project, the monthly value of KR averaged 0.30 with a standard deviation equal to 10% of the mean value. The difference between this location and that for the non-irrigated area is quite consistent with the effect of irrigation on mean temperature and the temperature range. It is, therefore, concluded that equation 7 is quite adequate for the entire project.

At Davis, California, ratios of Alta fescue grass ET divided by Ra were calculated for 21 months during which no rainfall was recorded. The average ratio (ET/Ra) was 0.378 with a standard deviation of 0.0264 or 7.0% of the mean ratio. For five day periods with no rain and mean temperature above 12°C, the average ratio of ET/Ra from the Davis lysimeter data was 0.363 with a standard deviation of 0.0567 or 15.6% of the mean ratio.

It is suggested that equation 3 be used to estimate PET at various locations and values of KR for equation 7 be locally calibrated. Whenever the standard deviation of ratios is in an acceptable range, equation 7 will provide a very simple and practical method for estimating crop water requirements.

POTENTIAL CROP EVAPOTRANSPIRATION

The potential ET of a given crop, ETC, is estimated from crop coefficients Kc. The equation for ETC for a given stage of growth is:

$$ETC = PET \times Kc \tag{8}$$

Values of Kc are given in Figure 1 and Table 2.

The values of ETC from equation 8 are an approximation of the amount of water required by the crop for ET in order to produce good yields. The total water supply must be somewhat larger than ETC to allow for the efficiency of water use and for unavoidable water losses. Good yields of various commercial agricultural crops are given in Table 3.

Doorenbos and Kassam, 1979, present a methodology for estimating the yield response to water or the yield reduction from reduced crop ET. Coefficients are presented for various stages of growth and for the growing season. There is significant variation in these coefficients, but on the average a 10% deficiency in supplying ETC produces a 10% reduction in yield. The actual reduction depends upon numerous interactions such as the crop stage during the period of greatest water deficit, the antecedent crop water stress, fertility available to the crop, presence or absence of salinity, etc.

YIELD RESPONSE TO WATER

If the other factors of production or crop yield are constant, then maximum yield, Ym, can be shown as a function of one variable, water or crop ET. The Stewart yield model from Doorenbos and Kassam, 1979, provides a means for estimating the crop yield response. The Stewart equation can be written:

$$\left(1 - \frac{Ya}{Ym}\right) = ky \left(1 - \frac{ETa}{ETm}\right) \tag{9}$$

in which Ya = actual harvested yield, Ym = maximum or potential

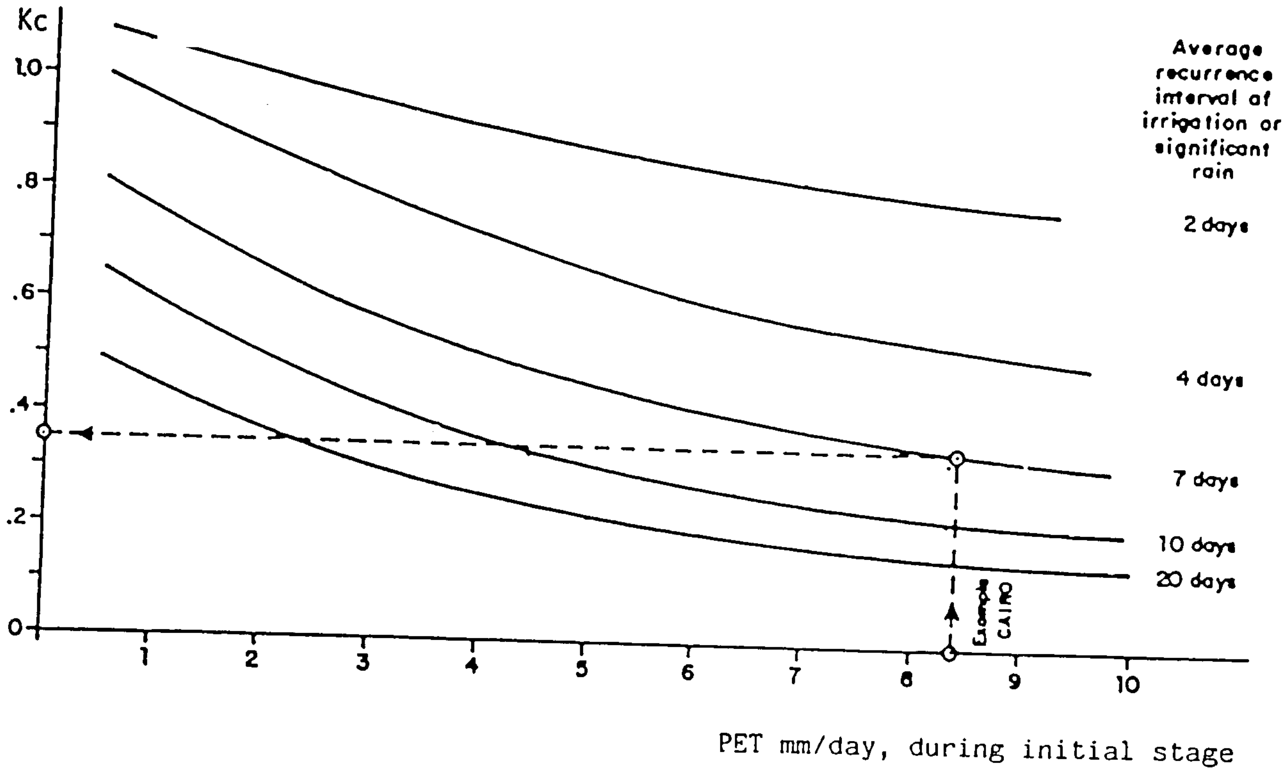

Figure 1. Average Kc value for initial crop development stage as related to level of PET and frequency of irrigation and/or significant rain.

Source: Doorenbos and Pruitt, 1977.

Table 2. Crop Coefficients (Kc).

CROP	Crop Development stages					Total growing period
	Initial	Crop development	Mid-season	Late season	At harvest	
Banana						
tropical	0.4 -0.5	0.7 -0.85	1.0 -1.1	0.9 -1.0	0.75-0.85	0.7 -0.8
subtropical	0.5 -0.65	0.8 -0.9	1.0 -1.2	1.0 -1.15	1.0 -1.15	0.85-0.95
Bean						
green	0.3 -0.4	0.65-0.75	0.95-1.05	0.9 -0.95	0.85-0.95	0.85-0.9
dry	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.75	0.25-0.3	0.7 -0.8
Cabbage	0.4 -0.5	0.7 -0.8	0.95-1.1	0.9 -1.0	0.8 -0.95	0.7 -0.8
Cotton	0.4 -0.5	0.7 -0.8	1.05-1.25	0.8 -0.9	0.65-0.7	0.8 -0.9
Grape	0.35-0.55	0.6 -0.8	0.7 -0.9	0.6 -0.8	0.55-0.7	0.55-0.75
Groundnut	0.4 -0.5	0.7 -0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
Maize						
sweet	0.3 -0.5	0.7 -0.9	1.05-1.2	1.0 -1.15	0.95-1.1	0.8 -0.95
grain	0.3 -0.5*	0.7 -0.85*	1.05-1.2*	0.8 -0.95	0.55-0.6*	0.75-0.9*
Onion						
dry	0.4 -0.6	0.7 -0.8	0.95-1.1	0.85-0.9	0.75-0.85	0.8 -0.9
green	0.4 -0.6	0.6 -0.75	0.95-1.05	0.95-1.05	0.95-1.05	0.65-0.8
Pea, fresh	0.4 -0.5	0.7 -0.85	1.05-1.2	1.0 -1.15	0.95-1.1	0.8 -0.95
Pepper, fresh	0.3 -0.4	0.6 -0.75	0.95-1.1	0.85-1.0	0.8 -0.9	0.7 -0.8
Potato	0.4 -0.5	0.7 -0.8	1.05-1.2	0.85-0.95	0.7 -0.75	0.75-0.9
Rice	1.1 -1.15	1.1 -1.5	1.1 -1.3	0.95-1.05	0.95-1.05	1.05-1.2
Safflower	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.7	0.2 -0.25	0.65-0.7
Sorghum	0.3 -0.4	0.7 -0.75	1.0 -1.15	0.75-0.8	0.5 -0.55	0.75-0.85
Soybean	0.3 -0.4	0.7 -0.8	1.0 -1.15	0.7 -0.8	0.4 -0.5	0.75-0.9
Sugarbeet	0.4 -0.5	0.75-0.85	1.05-1.2	0.9 -1.0	0.6 -0.7	0.8 -0.9
Sugarcane	0.4 -0.5	0.7 -1.0	1.0 -1.3	0.75-0.8	0.5 -0.6	0.85-1.05
Sunflower	0.3 -0.4	0.7 -0.8	1.05-1.2	0.7 -0.8	0.35-0.45	0.75-0.85
Tobacco	0.3 -0.4	0.7 -0.8	1.0 -1.2	0.9 -1.0	0.75-0.85	0.85-0.95
Tomato	0.4 -0.5	0.7 -0.8	1.05-1.25	0.8 -0.95	0.6 -0.65	0.75-0.9
Watermelon	0.4 -0.5	0.7 -0.8	0.95-1.05	0.8 -0.9	0.65-0.75	0.75-0.85
Wheat	0.3 -0.4	0.7 -0.8	1.05-1.2	0.65-0.75	0.2 -0.25	0.8 -0.9
Alfalfa	0.3 -0.4				1.05-1.2	0.85-1.05
Citrus						
clean weeding						0.65-0.75
no weed control						0.85-0.9
Olive						0.4 -0.6

First figure : Under high humidity (RHmin >70%) and low wind (U <5 m/sec).
Second figure: Under low humidity (RHmin <20%) and strong wind (>5 m/sec).

Source: Doorenbos and Kassam, 1979.

Table 3. Good Yields of High-producing Varieties adapted to the Climatic Conditions of the Available Growing Season under Adequate Water Supply and High Level of Agricultural Inputs under Irrigated Farming Conditions (ton/ha).

CROP		Climatic Regions					
		Tropics [1]		Subtropics [2]		Temperate [3]	
		<20°C [4]	>20°C	<20°C	>20°C	<20°C	>20°C
Alfalfa	hay	15		25		10	
Banana	fruit		40-60		30-40		
Bean: fresh	pod	6-8		6-8		6-8	
dry	grain	1.5-2.5		1.5-2.5		1.5-2.5	
Cabbage	head	40-60		40-60		40-60	
Citrus:							
grapefruit	fruit		35-50		40-60		
lemon	fruit		25-30		30-45		
orange	fruit		20-35		25-40		
Cotton	seed cotton		3-4		3-4.5		
Grape	fruit	5-10		15-30		15-25	
Groundnut	nut		3-4		3.5-4.5		1.5-2
Maize	grain	7-9	6-8	9-10	7-9		4-6
Olive	fruit			7-10			
Onion	bulb	35-45		35-45		35-45	
Pea: fresh	pod	2-3		2-3		2-3	
dry	grain	0.6-0.8		0.6-0.8		0.6-0.8	
Fresh pepper	fruit	15-20		15-25		15-20	
Pineapple	fruit		75-90		65-75		
Potato	tuber	15-20		25-35		30-40	
Rice	paddy		6-8		5-7		4-6
Safflower	seed			2-4			
Sorghum	grain	3-4	3.5-5	3-4	3.5-5		2-3
Soybean	grain	2.5-3.5		2.5-3.5			
Sugarbeet	beet			40-60		35-55	
Sugarcane	cane		110-150		100-140		
Sunflower	seed	2.5-3.5		2.5-3.5		2-2.5	
Tobacco	leaf		2-2.5		2-2.5		1.5-2
Tomato	fruit	45-65		55-75		45-65	
Water melon	fruit		25-35		25-35		
Wheat	grain	4-6		4-6		4-6	

1/ Semi-arid and arid areas only
2/ Summer and winter rainfall areas
3/ Oceanic and continental areas
4/ Mean temperature

Source: Doorenbos and Kassam, 1979.

harvested yield, ky = a crop yield response factor that relates the decline or decrease in Ya to the unit decrease in ETa; ETa = actual crop ET, and ETm = potential or maximum crop ET. Seasonal values of ky given by Doorenbos and Kassam average about 1.00, but vary significantly for different crops and for water stress in different growth stages.

Hargreaves, 1975, used yield data for several crops at various research locations to derive a yield function for relative yield, Y, as a function of total water (initial soil moisture, plus rain, plus irrigation). The range in the data was from 0.33 to 1.10 times full water adequacy. Y was assigned a value of 1.00 for maximum yield and X a value of 1.00 for the amount of water required to produce maximum yield. The best fit equation found for the available range of data used can be written:

$$Y = 0.8X + 1.3X^2 - 1.1X^3 \qquad (10)$$

Data were not available for the lower portion of the curve and the relationship for X less than 0.33 is undefined. An intercept of 0 was assumed to facilitate development of the equation. Subsequent research indicates that for several crops, X = 0.33 is approximately the lower limit for economical production and X = 0.45 the lower limit for economical applications of fertilizers. These limits will vary with the crop and several other factors, but can be used as a rough guide.

IRRIGATION EFFICIENCIES

The estimation of crop evapotranspiration is straightforward. However, the evaluation of irrigation efficiencies or uniformity of application may be rather complex. The irrigation efficiency of a sprinkler or drip system is more easily controlled and may be fairly constant throughout the growing season. In surface irrigation, the efficiency is influenced by soil type, plant root depth, length of the field, application rate, net irrigation depth, etc. Most of these factors are variable throughout the field or during the growing season. The efficiency may be very low at the beginning of the season due to a high intake rate and to a low advance rate of the water as well as to the shallow root depth of the crop.

In many large and important irrigation projects in India, Pakistan, Sri Lanka, Africa, and others, there is a large excess of irrigable lands and a limited amount of water. Farmers may find it desirable to stretch the water through deficit irrigation in order to irrigate more land and increase irrigation efficiencies. The desirable abount of deficit in irrigation will depend on the cost of production per unit land area, the crop value per unit yield and the crop reduction due to the deficit and to some other factors, such as the presence or absence of salinity. In many cases, it will be worth-while to evaluate the economics of deficit irrigation as probably as much loss of yield has occurred from over irrigation as from not having enough water.

DATA REQUIREMENTS

An analysis of the rainfed agricultural potential and of the needs and requirements for irrigation should be based on adequate and reliable climatic data. Frequently, data collection programs measure more variables than are necessary, yet fail to report the data required for a good agrotechnological analysis. Crop selection and potential crop yields are determined principally by temperature, PET and available water and also soils and fertility. As outlined above, temperature determines PET. For rainfed agriculture, rainfall indicates the potential water availability. Good agroclimatical analyses require daily records of maximum and minimum temperatures and daily rainfall. Without these data, a good evaluation of the agricultural potential is not possible. However, as indicated above, temperature can be approximated from nearby locations. Rainfall is so variable that is must be measured at each representative site. In one area evaluated, good water management will require rainfall measurements on each 100 hectare area.

Water availability depends on the amount, distribution, and intensity of rainfall. Monthly values provide rather incomplete information as distribution within the month and the intensity of short duration rains have large influence on water availability.

USING DAILY RAINFALL DATA

The availability of daily rainfall records provides flexibility in analysis. Usually, soil conditions are such as to buffer crop water requirements for weekly or for 10 days, and sometimes for longer periods. Various methods of analysis are available. The moisture availability index, MAI, can be developed for weekly or longer periods. Another procedure is to calculate the probability for each week of having rainfall exceeding 50% of PET.

More attention has been given to drought analysis than to the management of excessive or high intensity rainfall. Much damage and loss of production of agricultural crops results from excess water and the resultant waterlogging of the cropped area. A common cause of damage to structures and other features of development projects is failure to anticipate the probable intensity of short duration rainfall.

The average 24 hour extreme rainfall amount is approximately 1.13 times the extreme daily amount. Where daily records are available, a censored log-normal or partial series probability analysis can be made of the extreme daily events. This may be accomplished by plotting all daily rainfall events exceeding a pre-determined amount on log-normal paper.

As indicated by Hargreaves, 1981, Powell, Narayana, Bell and others have shown that depth-duration rainfall amounts vary with the fourth root of the time of duration, t. An analysis of considerable data from various rainfall regions indicates that the ratio of $t^{0.25}$ applies well from 0.5 to 96 or more hours.

Powell (cited by Hargreaves, 1981) and Hargreaves and Vogler, 1984, found that for return periods, T, of from 5 to 100 years the depth-frequency amounts vary with the fourth root of the return depth-frequency amounts vary with the fourth root of the return period or with $T^{0.25}$. Depth-duration-frequency rainfall amounts, D, can then be estimated by use of the equation:

$$D = K \times (T \times t)^{0.25} \qquad (11)$$

in which K is a coefficient for each location.

Adamson and Zucchini, 1983, compared eight different rainfall probability distributions for extreme storm rainfall amounts. For T = 10, the maximum difference between the probable amounts from these eight distributions is 9 percent. This indicates that the 10 year 24 hour rainfall amount (P 10, 24) can be determined from almost any of the probability distributions and the appropriate value of K calculated by dividing D by 3.94 which comes form $(10 \times 24)^{0.25}$.

The above methodology is not only useful for estimating flood damage and prabability of waterlogging, but also for ccomparing probable infiltration rate with rainfall intensities and for determining the needs and metnods for soil conservation practices.

Management of rainfall for rainfed agriculture and for optimizing its use under irrigation requires some knowledge of probable amount and distribution. Probability graphs are very useful. Four probability values for each month are adequate for defining the principal range of probabilities as illustrated in Figure 2. Graphs for each month may be drawn by hand or by computer. If the probabilities are calculated by computer, the incomplete Gamma distribution is preferred. If computer faccilities are not available, the ranking method is recommended.

PREDICTING DROUGHT AND FLOOD RISK

Figure 2 presents monthly probability distributions indicating the probable occurrence of excessive monthly rain or of extreme deficit. For each country or area, the probability analysis from long rainfall records can be used to define the relationship between the mean rainfall and the rainfall at a probability of exceeding a

Figure 2a. Begampet / August

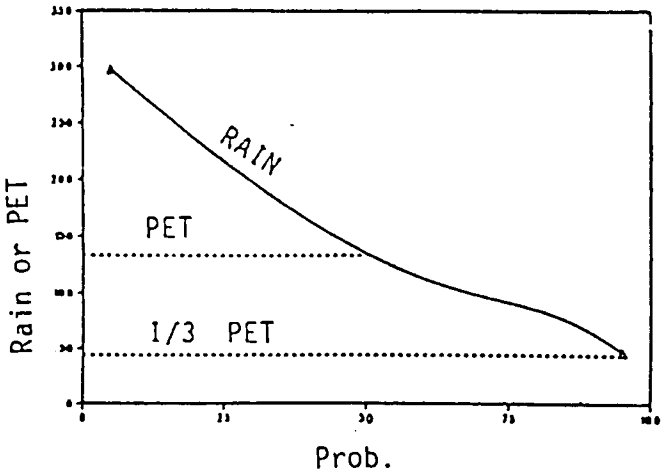

Figure 2b. Begampet / September

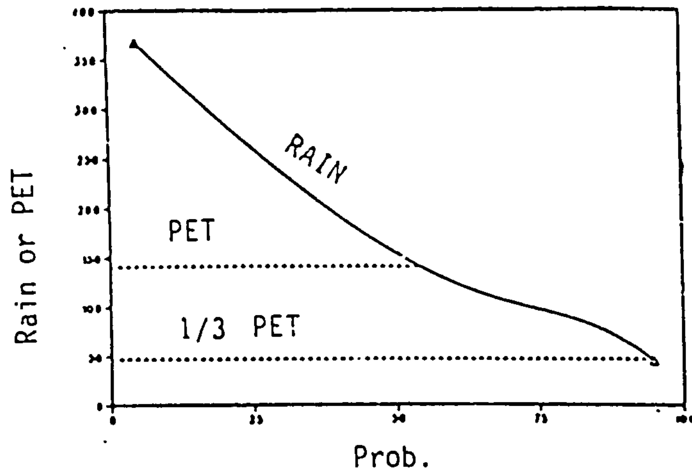

Figure 2c. Vishakhapatnam / August

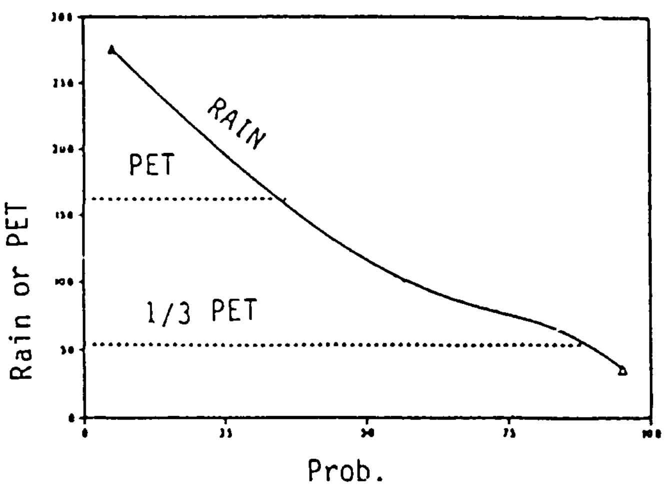

Figure 2d. Vishakhapatnam / October

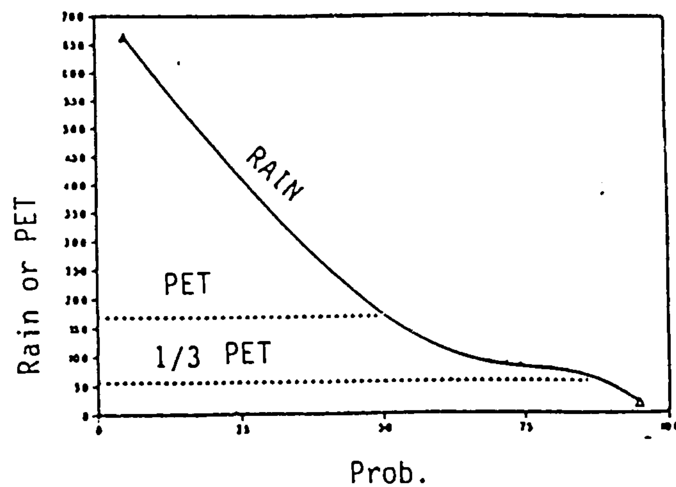

Figure 2. Probabilities of Assured Rainfall Compared with Estimated Values of PET and 1/3 PET for Selected Months at Begampet and Vishakhapatnam, Andhra Pradesh, India.

value x. Usually the correlations are significantly better if only those months with mean rainfall exceeding 50 mm are used. The general relationship is:

$$Px = a + b \times PM \tag{12}$$

in which Px = assured rainfall at the probability percentage x, a and b are regression coefficients and PM is mean monthly rainfall.

The 75 percent probability of assured rainfall, P75, correlates very well with mean monthly rainfall, PM, for most countries. The coefficients of determination. R^2, usually exceed 90%. Correlations for P05 and P95 are less reliable, but are often useful.

Appendix 3, Rainfall Probabilities From Average Values, presents a more accurate methodology for estimating the monthly probability distribution when only mean rainfall values are available.

Frequently, not enough attention is given to the estimation of unusual rainfall intensities and to probable flood damage. Flood prediction requires an evaluation of the probabilities of amounts of unusual or extreme rainfall. Appendix 4 presents a method or procedure for estimating depth-duration-frequency rainfall amounts from monthly rainfall records. The 20 year return period monthly amount (P05) is used as an index of rainfall intensities for durations of one half hour or more.

For drought and flood risk analysis the monthly probabilities are less than adequate. In various climatic regions known relationships are useful but lack precision. If the rainy season starts late and the amount during the first 30 days is low, it is often a good indication of a drought year.

A good analysis of drought probabilities requires a probability distribution analysis of rainfall for periods shorter than one month. Weekly or 10 day periods are recommended. The procedures outlined above and in Appensix 3 are recommended for use with these shorter time periods.

When a long-term series of monthly rainfall amounts is reported or published, it should include values of extreme daily amounts for each month. A probability distribution can be calculated in order to determine the value of P 10, 24 and of K in Equation 11. Extremes for other return periods and durations can be approximated from Equation 11. These depth-duration-frequency amounts should then be used with the rational equation or other acceptable flood prediction methods to evaluate the flood risk.

APPENDIX 1

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APPENDIX 2 - CALCULATING EXTRATERRESTRIAL RADIATION, Ra or RA

Calculating RA

RA (extraterrestrial radiation) can be calculated based on latitude of the station and the relative position of the earth to the sun.

If computer facilities are available, the computer program (Program I) can be used to calculate the average monthly values of RA. If daily values of RA are needed, then Program II can be used to calculate the daily RA.

Program I. Fortran computer equations for estimating monthly RA values.

Definition of Terms

ACOS = Arc cosine

DEC = Declination of the sun in radians

DL = Day length in hours (sunrise to sunset)

DM = Number of days in a month

ES = Mean monthly distance of the sun to the earth divided by the mean annual distance

LD = Latitude in degrees

LDM = Minutes of latitude

RA = Extraterrestrial radiation in mm per month

RAL = Mean monthly extraterrestrial radiation in Langleys/day

TM = Mean daily temperature in degree Celsius

```
DATA (DM(M), M = 1, 12)/31., 28., 31., 30., 31., 30., 31., 31., 30.,
*31., 30., 31./
DATA (DEC(M), M = 1, 12)/ -.3656, -.2365, -0.04682, .1607, .3247,
*.4017, .3699, .2360, .03995, -.1669, -.3291, -.4021/
DATA (ES(M), M = 1, 12)/.97104, .98136, 0.99653, 1.01313, 1.02625,
*1.03241, 1.02987, 1.01916, 1.00347, .98693, .97369, .96812/

C   CONVERT LAT TO RADIANS

XRL  =  (FLOAT(LD) + FLOAT(LDM)/60.)/57.2958
Z    =  -TAN(XLR) * TAN(DEC(M))
OM   =  ACOS(Z)
DL   =  OM/.1309
RAL  =  916.732* (OM * SIN(XLR) * SIN (DEC(M)) + COS (XRL)*
*COS  (DEC(M)) * SIN(OM))/ES (M)

RA   =  DM(M) * 10. * RAL/(595.9 - 0.55 * TM (M))
```

(from Hargreaves and Hargreaves (1))

PROGRAM II. FORTRAN COMPUTER EQUATIONS FOR ESTIMATING DAILY RA (Ra)

Definition of Terms

ACOS = Arc cosine

D = Julian Day (January 1 = 1)

DER = Declination (Angle of the sun) in radians

ES = Distance of the sun to the earth divided by the mean distance

LD = Latitude in degrees

LDM = Minutes of latitude

RA = Extraterrestrial radiation in mm/day

RLD = Extraterrestrial radiation in Langleys/day

TM = Mean daily temperature in degree Celsius

XLR = Latitude in radians

```
D     =  0
DO 8 K = 1,365
C 8 IS THE END OF THE DO LOOP
D     =  D + 1
Y     =  COS (0.0172142 * (D + 192) )
DER   =  0.40876 * Y
ES    =  1.00028 + 0.03269 * Y
XLR   =  (FLOAT (LD) + FLOAT (LDM)/60.)57.2958
Z     =  -TAN (XLR) * TAN (DER)
OM    =  ACOS (Z)
DL    =  OM/.1309
RLD   =  120. * (DL * SIN (XLR) * SIN(DER) + 7.639*COS
(XLR) *COS(DER) * SIN (OM) )/ES

RA    =  10. * RLD/(595.9 - 0.55 * TM)
```

Since the computer is not available in most developing countries, the following program was developed to be used in HP-15C calculators to estimate PET.

```
g RAD
R/S          lat     Rad
Sto 1
R/S          dec     Rad
Sto 2
R/S          ES
Sto 3
R/S          TMAX    C°
Sto 4
R/S          TMIN    C°
Sto 5
Rcl 1
TAN
Rcl 2
TAN
X
CHS
g COS -1
Sto 0        OM
Rcl 1
Sin
X
Rcl 2
Sin
X
Sto .1
Rcl 1
COS
Rcl 2
COS
X
Rcl 0
Sin
X
Rcl .1
+
916.732
X
Rcl 3
÷
Sto .2                 RLD
Rcl 4
Rcl 5
+
2
÷
Sto .3
0.55
X
CHS
595.9
+
1/X
Rcl .2
X
10
X
F PSE
F PSE
Sto .4                 RA, mm/day
Rcl 4
Rcl 5
-
√X
Rcl .4
X
Sto .5
Rcl .3
17.8
+
Rcl .5
X
0.0023                 PET mm/day
X
gRTN
```

Example

The following example describes how to use the calculator program to calculate PET.

Station Damien, Haiti

Lat. 18° 36'N

Month	January
Tmax	29.6
Tmin	18.8

Put the program in your calculator and then use the following steps:

Fn	n is the label of the program
0.3246	latitude in radian
R/S	
-.3656	Declination (Table 1 for January)
R/S	
.97104	Relative distance (Table 1 for January)
R/S	
29.6	Tmax
R/S	
18.8	Tmin
R/S	

and the program will calculate RA and the average daily PET for January.

RA = 11.56 mm/day

PET = 3.67 mm/day

For stations in southern hemisphere, the latitude should be entered as negative value.

TABLE 1

MONTH	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
DEC	-.3656	-.2365	-.04682	0.1607	0.3247	0.4017	0.3699	0.2360	0.03995	-.1669	-.3291	-.4021
ES	0.97104	0.98136	0.99653	1.01313	1.02625	1.03241	1.02987	1.01916	1.00347	0.98693	0.97369	0.96812

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APPENDIX 3 - RAINFALL PROBABILITIES FROM AVERAGE VALUES

Introduction

Daily or monthly rainfall values for individual years are often difficult to obtain, especially in developing countries. Often only the average monthly values are available. The International Irrigation Center has obtained monthly rainfall for individual years at nearly 3,000 locations. Average monthly data are reported by Wernstedt (8). This appendix presents a method for using average monthly data to estimate the various probability levels.

Development of the Method

The Gamma distribution function has often been used to analyze rainfall probability distributions (1, 2, 3, 4, 6).

The probability of rainfall in the Gamma distribution can be defined as:

$$P_x = \frac{\Gamma(y,u)}{\Gamma(y)} \qquad (1)$$

in which

P_x = the probability of rainfall exceeding the value of x or the assured rainfall at a percentage probability x, and

y = shape parameter of the Gamma distribution

The shape parameter (y) can be calculated as:

$$y = \frac{1}{4A}\left(1 + \sqrt{\left(1 + \frac{4A}{3}\right)}\right) \qquad (2)$$

where

$$A = \ln \overline{X} - \frac{\sum \ln x}{N} \qquad (3)$$

and

N = number of available data (total number of values in the data series)

$\overline{X}$ = Average rainfall

The parameter (u) in equation 1 is defined as:

$$u = \frac{x \cdot y}{\overline{X}} \qquad (4)$$

and

$$\Gamma(y) = \sqrt{\frac{2\pi}{y}}\ \mathrm{EXP}\,(y(\ln y - F(y))) \qquad (5)$$

in which

$$F(y) = 1 - \frac{1}{12\,y^2} + \frac{1}{360\,y^4} - \frac{1}{1260\,y^6} \qquad (6)$$

and

$$\Gamma(y,u) = \int_u^{\infty} t^{(y-1)} \cdot e^{-t}\, dt = \Gamma(y) - \int_0^u t^{(y-1)} \cdot e^{-t}\, dt \qquad (7)$$

substituting equation 7 into equation 1 will result:

$$P_x = \frac{\Gamma(y) - \int_0^u t^{(y-1)} \cdot e^{-t} \, dt}{\Gamma(y)} \qquad (8)$$

Equation 8 can be used to calculate the probability of exceedence (P_x) of rainfall (x), or the amount of rainfall (x) corresponding to a given probability form past records.

If only average rainfall ($\overline{x}$) values are given, first a relationship can be derived between average rainfall and rainfall at the 50 percent probability (X_{50}) using those stations with available long records. The general form of the relationship can be written as:

$$X_{50} = a + b\,(\overline{x}) \qquad (9)$$

in which a and b are calibration coefficients. Table 1 shows the parameters and coefficients of determination (R^2) of equation 9 for several countries.

The accuracy of equation 9 depends on the length of record and magnitude of monthly rainfall. Table 1 is developed based on long-term records of monthly rainfall with average rainfall with average values equal to or greater than 50 mm. Equations can be developed for months with average rainfall of less than 50 mm, but the correlation coefficients would be lower. For months with average rainfall of less than 50 mm, a second degree equation is often more appropriate. The accuracy of equation 9 can be improved if the countries or regions are divided in different climatological zones and the calibration coefficients for each zone estimated separately.

Rainfall at 50 percent probability can be estimated from equation 9, then the non-linear equation 8 can be solved to back calculate the value of the shape parameter (y). The shape parameter (y) is used to calculate the rainfall at other probability levels.

TABLE 1 - Calibration coefficients of equation 9 for different countries for months with average rainfall equal or greater than 50 mm.

Country	a	b	Degrees of Freedom DOF	Coefficient of Correlation R^2
Algeria	- 5.0	0.92	34	96.2
Brazil	- 8.9	0.959	460	99.0
Cameroon	-15.0	1.04	224	99.5
Central African Republic	-10.5	1.02	70	99.7
Chad	-11.1	1.01	56	99.4
Congo	-10.1	1.00	88	98.7
Ethiopia	-15.9	1.03	46	99.8
Guinea	- 8.12	0.963	170	99.6
India	-20.0	0.98	277	99.6
Indonesia	-18.6	0.972	149	98.0
Mali + Niger	-10.0	1.00	56	99.5
Mauritania	-14.2	0.994	16	91.0
Nigeria	- 9.61	0.982	63	99.3
Pakistan	-25.8	1.05	35	97.7
Senegal + Gambia	-16.0	0.994	52	99.4
Sudan	-12.5	1.02	52	99.2
South Africa	-13.5	1.03	46	99.8
Taiwan	-12.2	0.935	56	98.3
Zaire	-11.4	1.02	93	97.8

A computer program was developed at the International Irrigation Center to solve equation 8 for the shape parameter (y) through a Newton-Raphson technique and estimate the rainfall values for different probability levels.

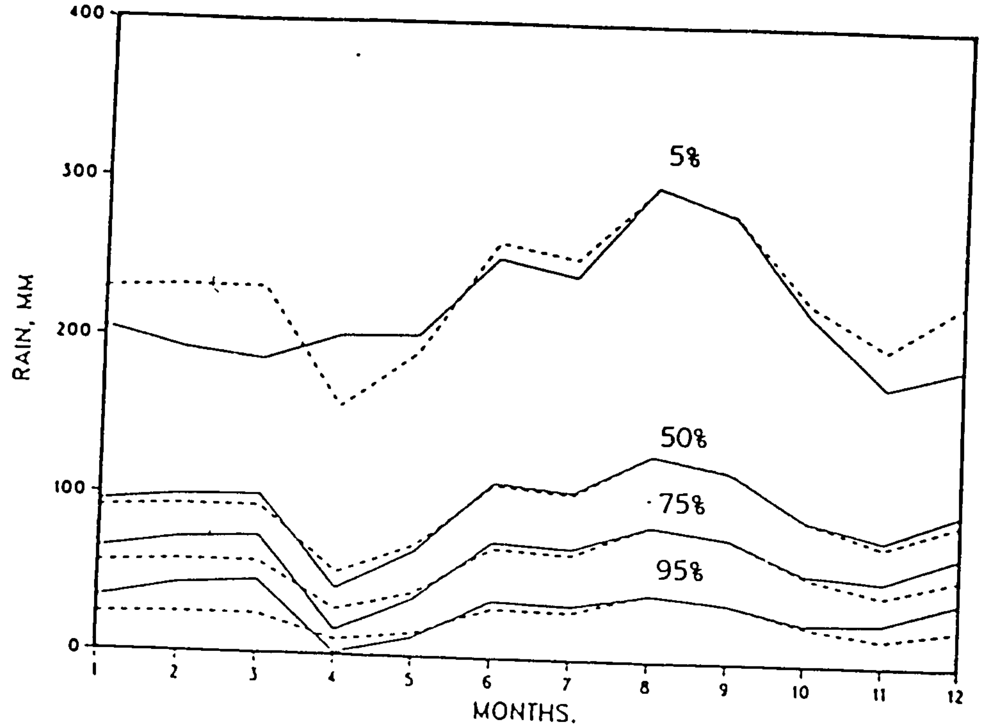
Testing the Method

Two countries (Brazil and India) were selected. In each country one station was taken at random. For each station, the assured rainfall at probability levels of 5, 50, 75, and 95 percent were calculated using the Gamma distribution function from past records. Then, assuming that only average values of rainfall are available, the rainfall for a probability of 50 percent were estimated using equation 9. The estimated value for the 50 percent probability was used in equation 8 to back calculate the shape parameter (y) of the Gamma distribution. After the shape parameter (y) was estimated, the rainfall amounts for different probability levels were estimated for each month. Figure 1 compares the calculated and estimated values of rainfall for different probability levels for each station.

The same technique can also be used with other distribution functions. However, some errors should always be expected in calculating rainfall probabilities. Samani and Hargreaves (7) found as much as 40 percent variation in calculating probabilities of rainfall due to the variation in length of record in northeast Brazil. Differences can also be expected depending on which distribution function is used to define the rainfall. Hargreaves (5) found that as much as a 15% difference in the probability level can be expected, depending on the distribution function which is used to define the rainfall.

The following program for the HP 15-C calculator back calculates the shape function (y) of the Gamma distribution using the average and 50 percent probability of rainfall and also calculates the rainfall at other probability levels:

ALEGRETE, BRAZIL



CALCUTTA, INDIA

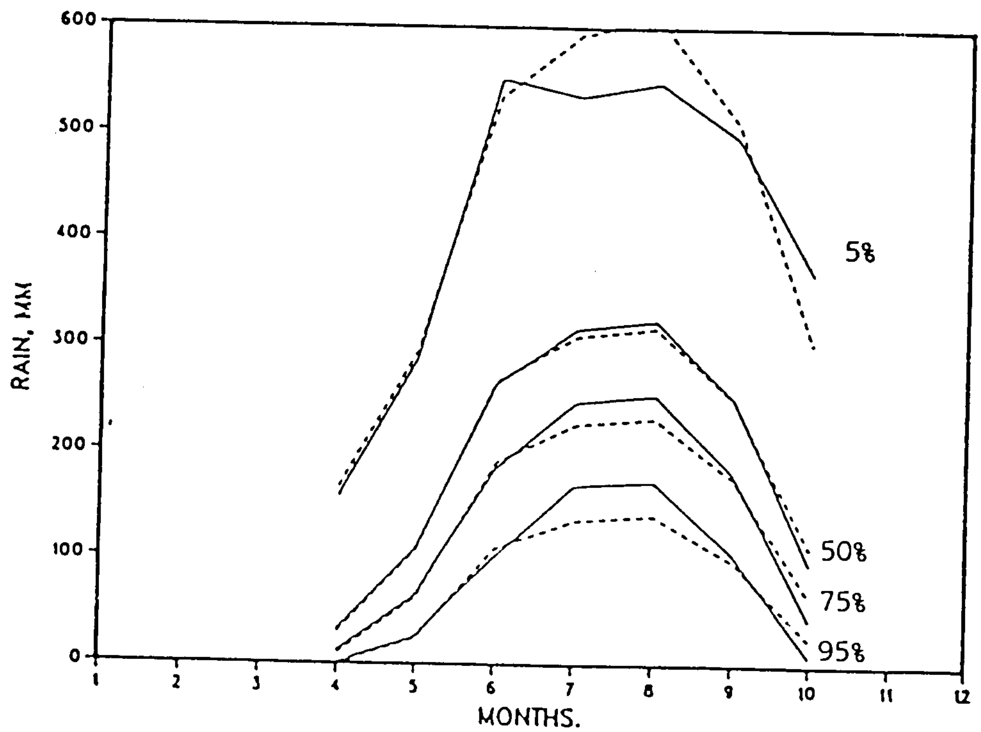


Figure 1 - Monthly Rainfall Probabilities, calculated from past records (solid lines) and estimated from average values (dashed lines).

Main Program

```
F LBL C
STO 1
RCL 0.0
RCL 1
÷
RCL 2
÷
1/x
STO 0.1
GSB D
RCL .2
RCL .1
F ∫E
RCL 3
-
CHS
RCL 3
÷
0.5
-
g RTN
```

Program for $\int_0^u t^{(y-1)} e^{-t} dt$

```
F LBL E
e^x
1/x
x⇄y
-
x⇄y
RCL 1
y^x
X
g RTN
```

Program for Γ (y)

```
F LBL D
RCL 1
1/x
STO 3
6
y^x
1260
÷
CHS
STO 4
RCL 3
4
y^x
360
÷
STO +
4
RCL 3
g x^2
12
÷
CHS
1
+
STO +
4
RCL 1
g ln
RCL 4
-
RCL 1
X
```

(cont)

```
e^x
STO 3
RCL 1
6.28
÷
1/x
√x
RCL 3
X
STO 3
g RTN
```

Example

For the month of January for the City of Brazilia (Brazil), the average value of rainfall (X) is reported as:

$\overline{X}$ = 251 mm

using equation (2)

R_{50} = 232 mm

The value of (y) can be calculated as follows:

0.0	Sto	0.2
251	Sto	0.0
232	Sto	2

3 Enter

4 (Initial estimates for y)

F solve C

The program will run and the value of (y) will appear on the screen.

y = 4.3467

then punch

F D

will solve for

Γ (y) = 9.427

$$B = \frac{251}{4.3467} = 57.745$$

if the probability of 100 mm rainfall is desired then

$$u = \frac{100}{B} = 1.7318$$

the next step would be

o Enter

1.7318

$F\int E$

will calculate

$$\int_o^u = 0.6372$$

and from equation 8

$$G\ (100) = \frac{9.427 - 0.6372}{9.427} = 0.93$$

Summary and Conclusion

A method is developed to estimate rainfall at different probability levels from average values. The rainfall at the 50 percent probability is estimated and by a back calculation technique, the shape parameter of the Gamma distribution is estimated using the Newton-Raphson technique. After the shape parameter is defined, the rainfall at other probability levels is estimated. The estimated values of rainfall at different probability levels have been locations compared with the actual calculated values at several locations. It is concluded that the method described above can be successfully used to estimate the range of rainfall probabilities from mean monthly values.

A calculator program for the Gamma probability distribution is presented. This program gives the basic elements so that a computer program can be written for these computations.

The following symbols are used in this Appendix:

a = Calibration coefficient

b = Calibration coefficient

DOF = Degrees of Freedom

e = 2.7183

N = Total number of values in the data series

P_x = Probability of rainfall exceeding the value of x

R^2 = Coefficient of Correlation

u = Gamma distribution parameter

x = Monthly rainfall in mm

X_{50} = Rainfall with 50 percent probability of occurrence

X = Average monthly rainfall in mm

y = Shape parameter of Gamma distribution

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APPENDIX 4 - EXTREME RAINFALL FOR SELECTED REGIONS

Introduction

In the design of drainage systems and hydraulic structures it is desirable that estimates be made of extreme rainfall amounts for various durations and return periods. Monthly rainfall amounts are more readily available than daily and much more available than intensities for shorter time periods. If monthly data can be used to estimate depth-duration-return period rainfall amounts, then significant improvements can be made in the planning of hydraulic works.

An evaluation was made of the relationship between the extreme daily rainfall for the period of record and the 5% probability of assured monthly rainfall based on long records. The relationship found is consistent with those documented in previous studies of depth-duration-frequency studies.

The Data Used

Monthly rainfall data for the world are available on computer tape from the National Oceanic and Atmospheric Administration (NOAA). Her Majesty's Stationery Office (various dates) gives values of the extreme daily rainfall amount for each month of record for those locations where these data were available. Extreme amounts were converted to extreme 24 hours amounts by multiplying by an average value of 1.13.

Procedure

The equation for depth-duration-frequency rainfall in terms of duration in hours (t) from 0.5 to a large number and return period (T) from 5 to 100 or more years is given by the equation cited by Hargreaves and Vogler (1984). The equation is:

$$D = K\ (t \times T)^{0.25} \qquad (1)$$

in which D is the depth of fall in time (t) and frequency (T).

Values of K were calculated by using the extreme daily rainfall for the entire period of record with t = 24 and T = the period of record. The daily values were multiplied by 1.13 to represent 24 hour extreme values. The calculated values of K were then compared with the 5% probability of assured monthly rainfall (P05). Only months with mean rainfall exceeding 100 mm were used. The equation can be written:

$$K = KP \times P05 \qquad (2)$$

For the value P05, the T equals 20 and t is 720. From equation 1 the value of K should be given by the equation:

$$P05 = K\ (20 \times 720)^{0.25} \qquad (3)$$

The equation for K would then be:

$$K = 0.091 \times P05 \qquad (4)$$

Values of KP were calculated for those locations where data were available. The results are as follows.

Location or Condition	KP
Coastal locations in Sumatra and Borneo in Indonesia	0.030
Along the major rivers of Brazil and in the lee of mountains in Costa Rica, Ecuador, Nepal, India and Peru	0.060
Makasar in Indonesia	0.065
Bangladesh, Ambonia in Indonesia, Port-au-Prince in Haiti and Kuala Lumpar in Malaysia	0.075
All of Africa, Pakistan, most of India, Sri Lanka and Panama	0.080
Singapore in Malaysia	0.090

Most of Brazil and Philippines	0.093
Calcutta and the Ganges Plain of India, Belize and Dili in Indonesia	0.100
The South Coasts of Caribbean Islands and Malacca in Malaysia	0.145

The value for Africa of KP = 0.080 is the average for 241 monthly computation. The standard deviation in the values was 34% of the mean value. This is considered to be very reasonable since at each location KP was calculated from one data point (the maximum daily rainfall for the period of record). This value could represent an outlier.

In locations where unusual rains may cause serious damage, it is probably desirable to increase the values of K calculated for use in equation 1 by at least a third. Particular caution needs to be given to hurricane rainfall. Amounts in the order of 19 or 20 inches in 24 hours have been recorded. Distruction of irrigation facilities during these extreme events has been fairly common in some locations.

Discussion

Hargreaves and Vogler (1984) found that equation 1 reproduced the values obtained from the censored log-normal distributions for rainfall periods of up to 7 days with a satisfactory degree of accuracy. It appears from the above analysis that equation 1 is satisfactory for most planning purposes for periods of up to at least several days. This tentative conclusion should be further evaluated using other data sets from differing climatic regions.

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