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COMPREHENSIVE REVIEW OF DROUGHT INDICES

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ABSTRACT

Scores of drought definitions are available in the literature developed by a variety of disciplines because it affects so many economic and social sectors. Drought holds different connotations to different people. The phenomenon of drought can be interpreted in various ways depending on the scientific field involved, purpose and type of water use and extent to which it is perceived to be an expression of water dificiency. Accordingly, droughts are broadly categorised as meteorological, agricultural and hydrological droughts. A comprehensive review of important meteorological, agricultural and hydrological drought indices has been made to assess their applicability and limitations so as to select a particular criteria of drought quantification and help in developing improved drought indices.

The available drought indices vary from simple rainfall indices based on various threshold values to complex indices based on the water balance approach and soil moisture models. Most of the indices but for few comprehensive indices appear to be adhoc and work in isolation. They consider either rainfall alone or take some account of soil water storage and loss of water from soil storage by evapotranspiration. It is not sufficient to go by the variability of total rainfall alone but also to analyse and understand spatial and temporal variability in hydrologic process as well as study demand patterns to analyse drought in a better perspective. An overall water availability index could be a better index of drought.

1.0 INTRODUCTION

Droughts are common and known from time immemorial whose references are available in history and literature. The problem of recurrent droughts adversely affecting domestic and industrial water supply, fodder and agricultural production in the recent past have emphasised the need for more research on the causes as well as development of suitable criteria and indices for studying drought characteristics. Drought basically being the situation of water deficiency remains one of the important areas of study in the present day of increasing water demand and limited water supply. The occurrence of drought is not only confined to low rainfall areas but it also visits high raianfall areas as well.

Scores of drought definitions are available in the literature developed by a variety of disciplines because it affects so many economic and social sectors. Drought holds different meanings to different people in different areas depending on their specific interests. The phenomenon of drought can be interpreted in various ways depending on the,

i) scientific field involved

ii) purpose and type of water user, and

iii) extent to which it is perceived to be an expression of water deficiency.

Accordingly there are meteorological or hydrological droughts; drinking water and/or agricultural droughts; mild, moderate or severe droughts and so on. Droughts can be classified on various other bases hither to not mentioned but it is of the contention that the disciplinary perspectives of drought include, about 150 definitions in literature (Wilhite & Glantz, 1985). Intrinsic within each definition is the fact that drought represents a negative departure from the expected water availability in relation to a particular need for the given area.

Regardless of the particular definition of drought adopted, a problem of utmost practical importance is the parameterisation of drought characteristics for a quantitative assessment of the severity, the spread of droughts together with the frequencies of their occurrence. This is the foremost step in the evaluation of the economic feasibility of the drought control or mitigation measurers. Hence the applicability of existing drought indices and development of appropriate "indices" is a necessary and essential pre-requisite in identifying drought and combating its ill affects. However, the measurement of drought severity and the determination of the threshold value which initiates the onset of drought spell have been no less varied than the myriad definitions of the phenomenon itself. Drought severity too is ridden with complications in its determination. It is not only dependent on the duration, intensity and geographical extent of a specific drought episode but also on the demands made by human activities and by the vegetation on a region's water supplies.

Clearly, the involvement of so many variables in the description of the phenomenon elucidates the fact that the concept of drought is highly variable . As a result conflicting definition arise, often leading to confusion among the decision makers about what constitutes a drought.

The confusion can lead to inaction, indecision and adhoc responses with little understanding of the social and environmental implications of these responses. Therefore, in this report efforts have been made to collect and review some important meteorological, agricultural and hydrological drought indices, assess their effectiveness and highlight their merits and demerits, so as to select a particular criteria of drought quantification for a given situation and help in developing improved drought indices.

2.0 DROUGHT INDICES - AN OVERVIEW

2.1 Concept and Definition

A large number of drought definitions and indices are available in the literature (Hounam et al, 1975; Subrahmanyam, 1967; Palmer, 1965 Sikka, 1984; Apparao, 1986; Ramakrishna, 1986; Das, 1986; and Wilhite & Glantz, 1985). It is evident from the literature that the notion of drought is relative. Drought has been frequently defined according to disciplinary perspective. Subrahmanyam (1967) indentified six types of drought - meteorological, climatological, atmospsheric, agricultural, hydrologic and water management. Some researchers have also defined economic drought. National commission on Agriculture (1976) broadly defined three types of drought-meteorological, agricultural and hydrological. The meteorologist is concerned with drought in the context of a period of below normal precipitation. To an agriculturist, drought means a prolonged shortage of soil moisture in the crop root zone. To a hydrologist, it means below average content in streams, reservoirs, lakes, tanks, ground water aquifers and soil moisture. The economist is concerned with drought in the context of period of low water supply which affects society's productive and consumptive activities.

The failure to develop a scientific and objective definition of drought has become one of the major obstacles to the analysis of droughts. Regardless of many specific discipline or user oriented definitions and concepts of drought advanced with the purpose to enable the objective identification, characterization and classification of droughts, all tend to agree that drought is synonymous with water deficit or water scarcity over a significant length of time and space. Yevjevich (1967) has rightly suggested that the mathematical analysis of the time and space distributions of water supply minus water demand (of selected drought defining variables) results in feasible way of establishing an objective framework in order to define and analyse drought for any particular use or interest in water resources. In the present context the mathematical formulation of the definition of drought is synonymous to a corresponding drought index of particular use or interest.

Regardless of the type of definition or index being used, droughts are analysed and characterised on the basis of following components:

- Magnitude (average water deficiency)
- Duratioan (period of water deficit)
- Severity (cumulative water deficiency)
- Frequency (probability of drought occurrence)
- Begining & ending of drought

2.2 Drought Characterising Variables

Droughts are analysed and characterised by a selected set of variable(s). The drought characteristics are random variables as their values change from one drought to another randomly. The variables generally used to define droughts are **rainfall**, temperature, evaporation, evapotranspiration, soil moisture, streamflow, reservoir/ tank levels and storages, ground water levels, crop parameters like critical growth stages and crop yields, fodder production, land use etc. The water demand defining variables like drinking & domestic water demand, live stock water demand, industrial water demand, crop water demand and other necessary water demand variables are user, location and interest specific and these may be relatively more problem oriented. Invariably, most of the drought indices consider the water demand variables in indirect way, if so.

2.3 Conceptual or Operational Drought Indices

Drought indices may be conceptual or operational based on whether they identify some boundaries or threshold of drought concept or identify various drought characteristics.

In the early days of the drought study, the phenomenon was generally regarded in conceptual terms. For exampale, drought was defined as "an extended period of dry weather, especially one injurious to crops (WEBSTER'S DICTIONARY, 1960)", a relatively temporary departure of the climate from the normal or average towards aridity" (Palmer 1957)". Any year in which the Nile river does not flood is considered a drought year regardless of rainfall " (Chow 1964). Evidently such conceptual definitions did not help in the identification of the onset of the drought periods, neither helped to determine the duration of water deficiency nor its impacts as the boundaries of the event were described ambiguously or arbitrarily. Such conceptual derfinitions were not preferred as they offered little assistance in analysing the severity of drought impacts. With the advent of improved methods of measurements of various drought defining variables, the significance of these variables gained recognition as a result of which the drought phenomenon came to be viewed in a better perspective. Subsequently improved versions of drought indices were formulated incorporatiang some of the important hydrologic variables associated with drought. Such indices can be used to determine not only the onset, duration and/or termination of a drought period but also used to analyse drought frequency, severity and duration for a given historical period. However these 'operational indices' require historic records of hourly, daily, monthly or seasonal moisture deficiency departures from normal i.e. the expected values in order to identify the drought characteristics.

An operational definition of drought for example, could be one that compares daily rainfall values to evapotranspiration rates to determine rate of soil moisture depletion after correcting for surface runoff, and expresses these relationships in terms of drought effects on crop growth at various stages of crop development.

Again a wide spectrum of drought definitions and indices can be generated on the basis of the large number of operational parameters involved. It is beyond the scope of the present report to present the entire multitude of the indices. On contrary, the discussion has been narrowed down to the analysis of indices obtained on the basis of the model of the hydrologic cycle of a given watershed system (for which the drought indices are applicable). Every model consists of three important components - input, the system and output. From the nature of model of the hydrologic cycle a drought event can be interpreted in terms of precipitation as the set of inputs, the watershed as the system and runoff as the set of outputs. In a broad sense, if one is interested in determining the causes of drought event then attention should be focussed on precipitation characteristics (alongwith other aspects of climate and the watershed system): if one is interested in assessing the impacts of the drought event then attention must be focussed on resulted stream flows (including reservoir storages), groundwater fluctuations and soil moisture characteristics. With the above distinctions, drought causes become the province of the meteorologists while the drought affects become the province of the hydrologist and the agriculturist (Dracup et al. 1980). Accordingly, the droughts have been classified into:-

- Meteorologic,
- Agricultural, and
- Hydrologic droughts.

2.4 General Tasks in Drought Analysis

Although conflicting concepts of drought are held by various academic fields, the following set of decisions are required to be considered for taking up a task of drought analysis in a more systematic and scientific perspective as indicated by Dracup et al. (1980).

2.2.1 Selecting nature of water deficit

The deficit may be in terms of streamflow or reservoir storages or groundwater levels (i.e. hydrological drought), precipitation (i.e. meteorologic drought), soil moisture (i.e. agricultural drought) or any combination of these. Accordingly the variable(s) which defines the drought phenomena are identified.

2.4.2 Selecting integral period of time

Integral period is the time period e.g., daily , weekly, 10 daily, monthly, seasonal, or yearly depending upon the purpose and type of study for which the hydrologic data is to be averaged for drought analysis or from which the minimum value for the period is picked.

2.4.3 Selecting truncation level

It is a threshold level to define or separate drought from other events. It divides a time series into above normal and below normal sections. This should also reflect the socio- economic demands on the available water supply. Generally, the investigators chose some measure of the central tendency of the drought sample e.g. mean, median and mode as the truncation level. The selection of truncation level is a function of the type of water deficit being considered. For example; mean soil moisture present during the growing season may be selected as a truncation level for analysis of agricultural droughts. The demand need not be constant and it can also be represented by some time varying truncation levels.

2.4.4 Regionalisation

The method of regionalisation is employed because droughts are inherently regional in nature, thus their areal extent is an important characteristics to be considered. Moreover, limiting the analysis to a single site is generally not feasible because of small sample size i.e. hydrologic record and in such cases regionalisation provides a means of increasing the sample size.

Although a complete analysis of a drought event would necessarily include consideration of rainfall, runoff, soil moisture and groundwater together, but most drought studies are observed to focus on only one aspect of the drought phenomenon and that is rainfall.

3.0 METEOROLOGIC DROUGHT INDICES

Precipitation forms the sole natural input component in the model of the hydrologic cycle of a watershed. It follows that the precipitation over an area or precisely the lack of it can be regarded as one of the main cause for drought to occur in the area. Hence, early workers considered drought to be predominantly a meteorological phenomenon and as a result of which the meteorologic definitions of drought are found to be the most prevalent in the available literature. In this section efforts have been made to delineate various meteorologic drought definitions and indices. Meteorologic drought characteristics have been found to be explained prominently by rainfall that too mainly the variability of amount although the latest advances in meteorological science emphasise on the use of other meteorological parameters like temperature, humidity, sunshine, radiation and wind alongwith rainfall in quantifying the drought.

3.1 Based Only on Rainfall Characteristics

3.1.1 Rainfall amount and duration of dry days

In the early days, droughts were defined solely on the basis of the duration of the dry period and the degree of dryness by considering some threshold values. The threshold values adopted to delineate the onset of drought periods in different countries varied extremely as the limits were governed by the corresponding climatic characteristics and type of use or interest. A variety of drought definitions came into reckoning and as these definitions were site specific a realistic comparison of drought characteristics amongst various affected regions was not feasible. However, these indices do not represent time and space variability.

Formulations of such drought indices in different areas in chronological order are summarised in Appendix I.

3.1.2 Rainfall statistics and anomaly

Subsequently the meteorological drought definitions were improved by interpreting the precipitation characteristics at a place with respect to its comparison with the correspondig long term average of that place. A commonly used simplest index has been to compare the depth of rainfall for a given period i.e. pentad, week, fortnight, month, season or a year with the long term mean or standard period normal value of the given duration. Dry periods can thus be designated when the ratio is less than unity. Drought severity would depend on the amount of current rainfall falling short by some percentage of normal corresponding to that place for that period. Ramdas et al. (1950) defined drought as a week with actual rainfall equal to half of the normal rainfall or less. A year was considered as drought affected when rainfall less than normal by twice standard deviation of the series. Appendix II enumerates the various definitions and the associated concepts developed in a chronological order by various investigators.

According to IMD, for example the meteorological droughts can be classified as below:

Percentage departure from normal rainfall	Intensity of meteorological drought
0.0 or above	No drought
0.0 or -25.0	Mild drought
-25.1 to -50.0	Moderate drought
-50.1 or less	Severe drought

Statistical analysis of a long record is carried out to derive long term mean, standard deviation and coefficient of variation (Cv) of rainfall. If annual or seasonal Cv of rainfall is 30% or more, the area is termed "drought prone". When Cv in any of the month is 50% or more, the area is termed drought prone (CWC, 1982). If probability of occurrence for 75% of normal annual rainfall is less than 80, the area is classified as drought prone.

The probability of occurrence of dry spells of short and long duration have been studied by Rao et al (1971), Ramana Rao et al. (1976), Victor and Sastry (1979), Correia and Bohra (1980). The sequences of dry and wet spells during the monsoon periods in India using the Markov chain model have been investigated by Chowdhary et al. (1984), Khambete and Biswas (1984), Ramakrishna et al .(1984) and others. Khambete and Biswas (1984) for example, used two state markov chain model of Ist order to evaluate sequences of dry and wet weeks during S-W monsoon over dry farming tract of Maharashtra and proposed an index of drought proneness based on parameters of this model.

$$DI = \frac{P \times P_1}{1 - P_o} \times 100 \qquad \ldots (1)$$

where, P_1 and $(1-P_o)$ are wet and dry sequences

The present status of research in the estimation of drought recurrence after the first half of the present decade indicates the attainment of a stage wherein stochastic models have been developed to evaluate the conditional probabilities of incidence of drought years and highlight the concept of drought proneness in better perspective.

3.1.3 Rainfall deciles approach

Gibbs (1964) pointed out that the common measures of central tendency and dispersion i.e. mean and standard deviation are often poor indicators of the probability of rainfall occurrence. On contrary, the square roots of daily, monthly and even annual rainfall amounts appear to be close to normally distributed. The mean and standard deviation of the square roots are found to describe the distribution of rainfall more accurately. Gibbs & Maher (1967) advocated a method of evaluating drought severity by calculating the limits of each ten percent (or decile) of the data from the corresponding cumulative frequency amount which is not exceeded by ten percent of totals, and so on. The fifth decile or median is the rainfall amount not exceeded on 50% of the occasions. Again, the decile ranges give the ranges of values between the deciles i.e. the first decile range is that below the first decile; the eighth decile range is between seventh and eighth deciles,etc.Figure 1 illustrates the concept in which the square roots of the rainfall totals are plotted on the abscissa and the frequency density on the ordinate. The decile range in which a particular rainfall occurs gives a useful indication of its departure from 'average' and the area under the curve for any given range of

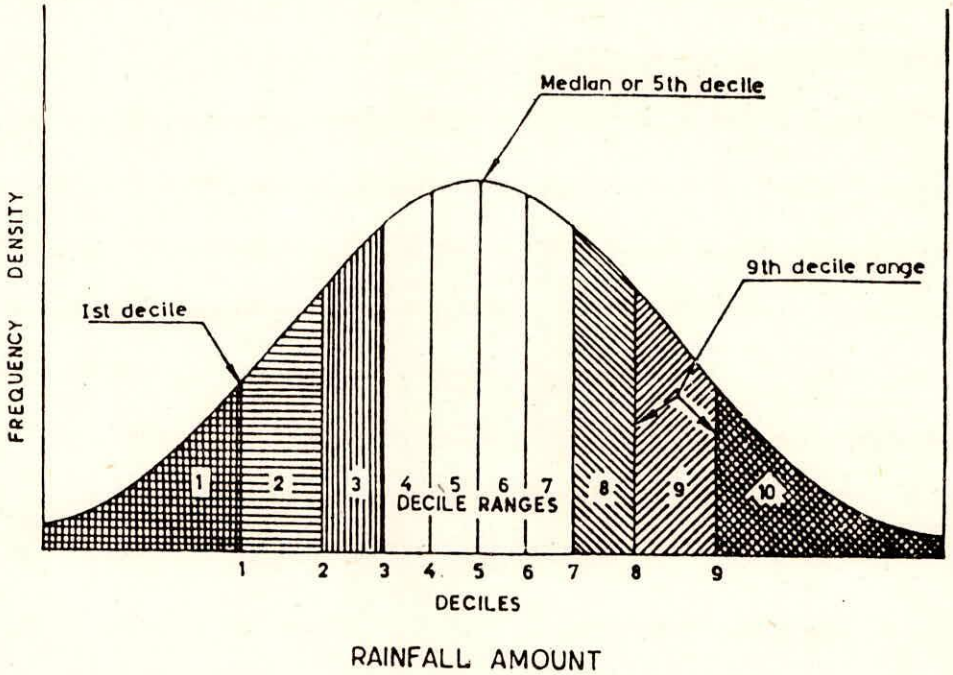

FIG.1 Illustrating use of deciles and decile ranges

rainfall indicates the frequency or the probability of occurrence within that range. 'Average' in this context refers to the most frequently occuring values grouped around the median rather than the arithmatic mean. The decile range one suggests abnormally dry and decile range ten abnormally wet conditions. The deciles of annual rainfall as drought indicators were found to effectively represent the conditions of droughts in Australia. The maps drawn using these data indicate the rainfall anomaly and the spatial distribution of the areas which were 'very dry' or 'very wet' in a particular year. This technique can be considered as an aid to provide approximate and preliminary indication of drought and manner of its coverage. George and Kalyansundaram (1969) adopted this method to study the droughts in Bihar using monthly rainfall deciles instead of annual deciles. Quantile rainfall amounts were reported by George et al.(1974).

3.1.4 Rainfall based numerical indices

(a) VanRooy Index

Van Rooy (1965), cited from Kalyansundaram and Ramasastri 1969) developed an anomaly index I from annual rainfall series and prepared maps showing the probability patterns of rainfall anomalies.

$$I = -3 \frac{(p - \bar{p})}{(\bar{m} - p)} \qquad \ldots (2)$$

where I = anomaly index,

p = actual precipitation,

$\bar{p}$ = long term average precipitation, and

$\bar{m}$ = mean of ten lowest values of p on record

The negative sign was introduced to indicate that the anomaly is negative. The factor $\bar{m}$ has been defined as the threshold value of the precipitation p ushering in the drought conditions. The limits of the variation of the index are given as:

Anomaly Index		Class description
	$\geq$ 3.00	Extremely wet
2.00	to 2.99	Very wet
1.00	to 1.99	Moderately wet
0.55	to 0.99	Slightly wet
0.49	to -0.49	Near normal
-0.50	to -0.99	Slightly dry
-1.00	to -1.99	Moderately dry
-2.00	to -2.99	Very dry
	$\leq$ -3.00	Extremely dry

Kalyansundaram and Ramasastri (1969) modified the Van Rooy's anomaly index to suit the Indian conditions in their study of drought in Bihar. The mean of the ten lowest values of the monthly precipitation p on record, $\bar{m}$ was assumed to be three-fourths of $\bar{p}$, the normal precipitation. Frequencies of the cumulative drought indices within the specified ranges were worked out. This index is also based on rainfall amount alone and do not consider its duration.

(b) Herbst method

Herbst et al.(1966) developed a technique for evaluating droughts by using monthly raianfall data. The technique determines the duration and intensity of droughts as well as the months of their onset and termination . It also permits the comparison of drought intensities irrespective of their seasonal occurrence. This technique was used by investigators to study severity of 1975-76 drought in England and Wales mainly due to its complete objectivity in identifying significant periods of rainfall deficiencies.

Criteria and parameters involved:

M_t = Mean rainfall for a month (t = 1 to 12)

MAR = Mean annual rainfall = ΣM_t

W_t = Weighting factor

$$= 0.1 \left(1 + \frac{M_t}{(1/12)\ MAR}\right) \qquad \ldots (3)$$

This weight factor is used to evaluate carry over from one month to the other.

Excess or Deficit = $A_t - M_t$

A_t = Actual Rainfall

Effective raianfall

$$E_t = A_t + W_t(A_{t-1} - M_{t-1}) \qquad \ldots (4)$$

This is calculated for each month

(carry over for first month zero)

$(MMD)_t$ = Mean Monthly deficit

$$= \frac{\Sigma\ (E_t - M_t)}{n}$$

for surplus i.e. negative deficits this is zero

MAD = Mean annual deficit = $\Sigma\ (MMD)_t$

= Maximum M_t = MMMR

D = Duration in month

A first indication of the seriousness of drought is given by a measure of drought intensity. The average monthly drought intensity related to the sum of the monthly mean defects over the same duration gives an intensity index

$$Y = \frac{\sum_{t=1}^{D} [(E_t - M_t) - (MMD)_t]}{\sum_{t=1}^{D} (MMD)_t} \quad \ldots (5)$$

Severity of drought is given by following index

$$\text{Severity index} = Y \times D \quad \ldots (6)$$

Test for beginning a drought

This is based on comparison of sum of consecutive deficits with a sliding scale MMMR, MMMR + x, MMMR + 2x,....MMMR+ 11x

A parameter x can be defined as

$$x = \frac{MAD - MMMR}{11} \quad \ldots (7)$$

first month with a deficit for which $(E_t - M_t)$ is negative is start of potential drought:

If the deficit $(E_t - M_t)$ = MMMR , a drought begins

If $(E_t - M_t)$ = MMMR (i.e. < MMMR)

and $(E_{t\pm1} - M_{t\pm1})$ is negative

Then, if $(E_t - M_t) + (E_t \pm 1 - M_{t\pm1}) \geq MMMR + x$

drought is said to begin from month t.

Sequential sums of deficits from t or t + 11 tested against scale and

whenever $\sum^{n}$ Deficits > MMMR + (n-1)x

a drought begin from t

If the algebric $\sum (E_t - M_t)$ is +ve, potential drought is ended. Testing can again be started from next month with a deficit.

Test for ending a drought

It is applied as soon as 1 month $(E_t - M_t)$ is +ve after the start of a drought.

(A) One of $(E_{t\pm1} - M_{t\pm1})$ and $(E_{t\pm2} - M_{t\pm2})$ must be +ve. If this is not shown by result we have to start this with 2nd month with +ve difference (surplus)

(B) If algebric $\sum^{n} (E_t - M_t)$ is negative before termination by next test then drought only interrupted

(c) Ten sequential tests

i) If $(A_t + A_{t+1} + A_{t+2}) > \Sigma$ (3 highest M_t)

drought is terminated

ii) If not, then test if

$(A_t + A_{t+1} + A_{t+2}) > \Sigma$ (4 highest M_t) , and so on until

$$\Sigma (A_t + A_{t+1} + A_{t+2} + \ldots. A_{t+11}) > \Sigma (M_t) \quad t = 1 \text{ to } 12$$

By this stage drought has terminated and is ended in the month where the multiple test started or drought has resulted after interruption.

This method was adopted by Das et al. (1977) in computing monthly drought hazards/intensities for classifying monthly as well as annual droughts in India at Ootacamund as given below:

Drought Class	Monthly value of drought intensity limit	Total monthly or annual drought intensity
Moderate	Upto 0.5	Upto 6
Large	Upto 0.75	Upto 9
Severe	Upto 1.0	Upto 12
Disastrous	Above 1.0	Above 12

c) Monthly rainfall anomaly index

Bhalme and Mooley (1981) developed numerical drought index based on monthly monsoon rainfall and duration for assessment of drought intensity. The drought intensity equation developed is givend as

$$I_k = 0.5\ I_{k-1} + (M_k/48.55) \qquad \ldots (8)$$

where

I_k & I_{k-1} are drought indices for K & K-1 month,

M_i is standardised measure of rainfall deficiency given as

$M_k = 100\ (R - \bar{R})/\sigma R$

Where R is the mean raianfall with mean $\bar{R}$ and standard deviation R

To begin the computations for the monsoon months (June-Sept) $I_o = 0$ for May was assumed. The reasons for setting $I_o = 0$ are not very clear. A drought Area Index (DAI) has been defined as the percentage of area having the mean monthly monsoon index $\bar{I} \leq -2$, where $\bar{I}$ is a weighted average of all indices from June to September. Though the criteria is somewhat arbitrary, but it has the advantage of taking into consideration the variance of raianfall which simple procedures or indices do not have.

(d) Precipitation deficiency index

Precipitation deficiency index developed by the Australian Bureau of Meteorology has been modified and being applied to U.S. Climate division data. Method depicts 3 basic categories:

1. Locations experiencing SERIOUS precipitation deficiencies
2. Location experiencing SEVERE precipitation deficiencies, and
3. Locations where a previously existing deficiency has ended

The "PRECIP" represents the accumulated precipitation at a site over the past 3 months. A SERIOUS deficiency is defined to exist when when:

Lowest 50% of Site's Historical record < "PRECIP" $\leq$ Lowest 10% of site's historical record

A SEVERE deficiency is defined to exist when:

"PRECIP" $<$ Lowest 5% of site's historical record

Deficiency is said to be ended when either of the following occurs:

i) Precipitation for the past month is already sufficient to put it in the highest 70% of previously recorded totals for the 3 month period starting with that month

or

ii) Precipitation for the past 3 months is among the highest 30% of previously recorded totals for the corresponding 3 month period

Modification to this index include:

Using the Gamma probability distribution and inclusion of an indicator for abnormally high monthly precipitation.

The index is reported to have produced results which are comparable with existing drought indices being used in U.S.A. .

3.2 Indices Based on Rainfall and Temperature

Efforts made to delineate the drought periods from the normal ones with the help of rainfall characteristics alongwith temperature have been reviewed in this section. Appendix III enumerates various drought definitions based on raianfall and temperature parameters in a chronologic order. In addition to this, the prediction of drought incidence through the study of radiation parameters and solar activity has been attempted by Choudhary et al. (1979 & 1984) by conducting energy budget studies. Departures from the normal values of the total global radiation were evaluated and analysed in order to determine the relationship between the spatial distribution pattern of the radiation with the incidence of drought.

3.3 Based on Aridity and Humidity Indices

The indices based on the statistical analysis of rainfall and temperature records, however lack the physical basis. On the other hand, the indices based on the climatic water balance method are widely accepted as the method is based on some phyhsical approach. The principle of the water balance approach is basically to integrate the moisture distribution in space and time.

The aridity index (Ia) of Thornthwaite (i.e. percentage ratio of annual water deficit to annual water need) based on Thornthwaite & Mather (1955) book keeping climatic water balance procedure first used by Subrahmanyam & Subramaniam (1964) is one amongst the most widely used indices describing the drought characteristics. The aspect of drought proneness is essentially delineated with the help of the magnitude of water deficiency from normal. It is evaluated with the help of a hypothetical meteorologic quantity - potential evapotranspiration or the water need. Potential evapotranspiration is defined as the water loss from a vegetation cover that never suffers from lack of water. It is a theoretical value depending primarily on the energy radiated from the sun due to which evaporation of water takes place. The severity, given by the magnitude of water deficiency at a place is determined by the difference between the corresponding potential and actual evapotranspiration values during the study periods.

$$\text{Aridity Index } I_a = \frac{\text{Water Deficit}}{\text{Water Need}} \times 100 = \frac{PE-AE}{PE} \times 100 \quad \ldots (9)$$

Where PE & AE are potential and actual evapotranspiration of the areas for the given period eg. weekly/monthly/seasonal.

Generally, using values of precipitation (P) and PE, the values of water deficiency are calculated using the water budgeting procedure of Thornthwaite & Mather (1955).

The normal valaues of aridity index (Ian) for the given period using long term values of P and PE can be estimated by knowing normal water deficiency and normal PE. The departures of actual aridity index (I_a) from normal aridity index (Ian) can thus be computed. The negative departures (aridity anomalies) for the given period are indicative of drought. These anomalies, when successively determined and added together algebrically over a specified period say monsoon season or year, give the cumulative negative departures. These aridity anomalies for different stations (week-wise or monthwise) are plotted to draw isolines and also to monitor drought as being done by IMD by publishing aridity anomaly maps of the country (Appa Rao et. al., 1981 & 1983).

The classification of drought intensity based on the magnitude of departures have been suggested by various workers. Subrahmanyam & Subramaniam (1964) while working out annual aridity index in the semi-arid region of South India suggested some criteria for drought classification based on a purely statistical approach and this approach was used by many workers to study climatological drought. Subsequently, Sastri and Ramakrishna (1980) found that this criteria do not hold good for the arid zone of Western Rajasthan as it does not indicate occurrence of any disastrous droughts even if the annual rainfall is nil or a few millimeters and disastrous conditions actually prevailed. They modified the earlier scheme of drought classification to suit to Rajasthan as presented below :

Departure of aridity index from normal (Subrahmanyam & Subramaniam (1964))	Departure of aridity index from normal (Sastri & Ramakrishna (1980))	Drought Intensity
Less than 1/2 σ	Less than 1/2 σ	Moderate
1/2 σ to σ	1/2 σ to σ	Large
σ to 2 σ	σ to $1\frac{1}{2}\sigma$	Severe
Greater than 2 σ	Greater than $1\frac{1}{2}\sigma$	Disastrous

The intensity of drought for the whole rainy season can be classified based on the mean departures of I_a from I_{an} using following criteria (Ramakrishna, 1986):

Range of mean $I_{an} - I_a$ for the rainy season	Drought intensity
0 - 10	Mild
11 - 20	Moderate
More than 20	Severe

The method of aridity index has been used extensively for meteorological & agricultural drought as well with little modifications in classifying the drought intensity using book keeping water budget approach of Thornthwaite (Subrahmanyam & Sastri, 1968, 1971; Krishnan & Thavi, 1971; Chowdhary et al., 1977; Subramaniam & Rao, 1982; Sarma & Ravindran, 1982 and many others).

The moisture index, I_m (humidity index, I_h - aridity index, I_a) gives a rough estimate of the moisture status of a region and is some times used to study frequency of droughts (Seth et al., 1979).

$$I_m = \frac{\text{Annual moisture surplus - Annual water deficit}}{\text{Annual water need}} \times 100$$

... (10)

Maps depicting the changing patterns of aridity and moisutre indices are good tools to study the sequential drought situation and cumulative deviations of moisture deficiency on a broad scale as a rough estimate to monitor meteorological drought. Aridity index approach has been widely used to study agricultural droughts also.

The Thornthwaite and Mather water balance approach being used assumes that AE is equal to PE when precipitation is equal to or greater than PE and AE is equal to precipitation plus soil moisture lost during that period when precipitation is less than PE. But, actually AE rather appears to be closely dependent on the soil moisture. It also relies on the threshold assumption that the water surplus (runoff + deep drainage) would exist only after the soil has attained its field capcity. Whereas, the method proposed by Budyko (1963) as described and modified by Sellers (1965) considers the variation of AE with respect to critical soil moisture content and also assumes that water surplus is proportional to precipitation and average soil moisture content during the period. This approach appears to be more logical and better suited for short interval computations eg. weekly etc., whereas Thornthwaite and Mather approach may not produce good weekly water balance computations because of their inherent limitations. In a drought analysis of Bikaner by Sikka (1986) the Budyko-Seller's model has yielded some amount of water surplus (runoff + deep percolation) during the rainy months July, Agust and September which appears to be logically true also as the rainafall is largely received in high intensity storms which may produce surface runoff. However, the climatic water balance studies done by early workers using Thornthwaite and Mather approach do not show any amount of water surplus even during the rainy months. There is a need for development of an improved hydrologic water balance technique for drought studies.

3.4 Palmer Drought Index

The Palmer Drought Severity Index (PDSI) developed by Palmer (1965) is the primary tool currently used by federal agencies in U.S.A. to describe prevailing drought conditions. Palmer defined a drought period as "an interval of time, generally of the order of months or years in duration during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply". Based on this definition, rational, systematic and objective approach for evolving the meteorological drought index as a single numerical value which represents the severity of drought incidence was developed. The main purpose of developing this index was to derive a general methodology for evaluating the meteorological anomaly in terms of an index which permits the time and space comparisons of drought severity . PDSI is definately an improvement over the Thornthwaite's aridity index in that it accounts the aspects of runoff and soil moisture characteristics with due corresponding weightages, which the latter does not. However, the development of drought index is too complex to take full account of all the pertinent physical and biological factors (Alley, 1984).

Based on the criteria for water budgeting, Palmer used the difference between the actual precipitation and the required precipitation under conditions of average climate in an area to evaluate the drought severity in space and time over the study area. The method incorporates the precipitation, potential evaporation (Thornthwaite method), antecedent soil moisture conditions and the available soil moisture and runoff values. Palmer considered the effective soil as made up of 2 layers viz., surface layer with 25 mm of available moisture and underlying layer of available moisture depending upon the water holding capcity of the soil. Instead of long term mean values, Palmer used CAFEC values (i.e. climatically appropriate for existing conditions) to find precipitation anomalies. The various coefficients have been used to convert mean values into CAFEC values. An emipirical weighting factor and drought severity equation has been used to analyse drought.

The detailed computational procedure developed by Palmer can be found in George et al. (1973), WMO (1975) and Sikka (1984). Utilizing the Thornthwaite system for calculating potential evapotranspiration, Palmer developed a series of equations for determining "Climatically Appropriate For Existing Conditions" (CAFEC) formulae, for: evapotranspiration (ET), soil moisture recharge (R) , runoff (RO), and moisture loss (L) . Adhering to the concept of supply and demand, he gave following equation

$$\hat{P} + \hat{L} = \widehat{ET} + \hat{R} + \widehat{RO} \qquad \ldots (11)$$

The CAFEC precipitation ($\hat{P}$) is computed for each month from the formula and then compared with actual precipitation which provides Palmer's monthly departure index d ($d = P - \hat{P}$). The value d, multiplied by appropriate monthly weighting factors, yields the moisture anomaly index.

The moisture anomaly index classifies the station into one of the following categories for the month under consideration:

		≥ 4.00	Extremely wet
3.00	to	3.99	Very wet
2.00	to	2.99	Moderately wet
1.00	to	1.99	Slightly wet
.50	to	.99	Incipient wet spell
.49	to	-.49	Near normal
-.50	to	-.99	Incipient dry spell
-1.00	to	-1.99	Mild drought
-2.00	to	-2.99	Moderate drought
-3.00	to	-3.99	Severe drought
		≤ -4.00	Extremely drought

The PDSI which is basically an index of meteorological drought is used extensively in the U.S.A. and published monthly in the Weekly Weather and Crop Bulletin to delineate the areal extent, severity of droughts and to assess drought impacts. In India, George et al. (1973) carried out drought analysis for 150 meteorological stations for the period 1970-71 to study incidence of droughts using PDSI employing Thornthwaite's method of computing potential evapotranspiration. The PDSI values compared nearly well to crop yields and well known recorded drought spells in Bihar and Tamilnadu. It is, however, noticed that the frequency and duration of drought months were cosnsiderably magnified in their study. For instance 20 to 25% occasions in each of the month of Kharif season turned out to be drought months for most of the sub-divisions of India. Percentage occurrence of droughts of class moderate and above in Kharif season have been given in Table 1. This over estimation may be due to non applicability of emipirical weightage factor originally developed for semi arid and dry

Table 1. Percentage Occurrences of Droughts of Class Moderate and Above in the Kharif Season

Sl. No.	Sub-division	June	July	Aug	Sept	Oct	Nov
1.	Coastal Andhra Pradesh	18	16	24	15	19	13
2.	Telangana	22	17	19	22	30	30
3.	Rayalaseema	24	28	30	27	27	27
4.	Tamilnadu	20	22	23	23	21	17
5.	Interior Mysore South	20	15	19	15	23	20
6.	Interior Mysore North	25	23	29	26	30	29
7.	Madhya Maharashtra	20	27	25	23	31	30
8.	Marathwada	25	23	25	23	30	25
9.	Vidarbha	20	20	24	21	25	24
10.	Gujarat	25	15	13	20	27	25
11.	Saurashtra-Kutch	22	25	25	30	35	31
12.	Uttar Pradesh East	20	27	20	25	25	27
13.	Uttar Pradesh West	18	17	18	18	22	20
14.	Punjab-Haryana	22	17	25	25	27	27
15.	Rajasthan East	33	25	25	30	38	37
16.	Bihar Plane	18	17	11	17	14	18
17.	Bihar Plateau	17	24	23	13	17	21
18.	Madhya Pradesh East	17	13	13	17	21	18
19.	Madhya Pradesh West	23	22	20	21	25	30

sub-humid regions of the U.S.A. Further, it is noticed that the frequency of incidence of moderate and severe droughts in arid zones of Rajasthan is shown to be lower than those of other divisions which probably may not be true. This may be due to the considered abnormalities in evapotranspiration, soil moisture and runoff as well, which are appropriate for the area.

Bhalme and Mooley (1979) reported that PDSI failed to explain the well known 1918 drought in the country. It was also observed that the weighting factor for July in respect of Chanda district was even negative and the defective weighting factor changed the sign of the moisutre departure. They introduced modified weighting factor and severity equation using data of 21 districts of the country. In subsequent studies, Rao and Subramaniam (1986) further suggested modifications in PDSI for analysing meteorologic drought in Maharashtra. Their contention of making modification in weighting factor was due to using of Penman's equation for PE. They used data of 23 stations in Maharashtra to develop weighting factor. Their modified severity equation is claimed to give relatively higher weightage to the current moisture anomaly as compared to Palmer's equation.

The drought severity index (PDSI) was originally **developed** as an index of meteorological drought. Palmer considered drought as a meteorological anomaly characterised by a prolonged and abnormal moisture deficiency. The PDSI gives long term anomalies as it has capability to trace back. It depicts prolonged periods (months, years) of abnormal dryness or wetness, responses slowly, changes little from week to week and reflects long term moisture, runoff, recharge, deep percolation and evapotranspiration. The drought severity maps are used in USA for measuring effects of prolonged dryness or wetness, identifying drought affected areas and reflecting the long term status of water supplies in aquifers, reservoirs, streams etc. Therefore, it is sometimes being used as a measure of hydrological drought also. It has the limitations of use in agricultural drought studies as it does not provide short term status of drought or wetness. Although the PDSI assumes that the capacities of the two soil layers are independent of seasonal or annual changes in vegetation cover and root development, however the temporal changes are of significance, especially in cul... ted areas.

It appears that Palmer's index does portray general changes in the moisture or water availability status, but it lacks sensitivity to short time period changes. The validity of using the PDSI to assess agricultural drought impact is questionable as plant response was not considered in the derivation of the index, nor does it figure in the calculation of index value. The overall usefulness of the index is a subject of debate.

A drought index, the measure of negative moisture anomalies from mean moisture status, using Thornthwaite's water budget approach was developed by Shear & Steila cited from Steila, undated in Arizona, USA.

$$\text{Drought Index (DI)} = MS - \overline{\overline{MS}} \qquad \dots (12)$$

$$MS = ST_o + (P - PE)$$

Wshere MS is monthly moisture status,

$\overline{\overline{MS}}$ is mean monthly moisture status of an area,

ST_o is soil moisture storage at the begining of the measurement period

P is precipitation during that period, and

PE is potential evapotranspiration of that period.

Drought in this study was defined as an interval of time during which the actual moisture status (MS) of a given place falls short of the mean moisture status appropriate for that location and time of the year. The magnitude of drought is a function of duration and intensity of the monthly deficiency. The categories of droughts proposed are as below:

Drought Index	Drought Intensity
-1.00 to -1.99	Mild drought
-2.00 to -2.99	Moderate drought
-3.00 to -3.99	Severe drought
$\leq$ -4.00	Extreme drought

The proposed drought index do not attempt to analyse agricultural drought. However, it does indicate certain relationship between moisture stress ranges and the physical condition of vegetation. The choice of limits are arbitrary.

4.0 AGRICULTURAL DROUGHT INDICES

4.1 General

Agricultural drought indices have been developed and used by many workers and most of them either link rainfall deficiency to agricultural impacts or soil moisture deficit or moisture stress to crop yields. A more meaningful definition of agricultural drought is the situation when soil moisture in the crop root zone and rainfall are inadequate to support healthy crop growth during any part of the growing season leading to water stress, crop wilt and damage of the crops. Availability of useful moisture to crop could be a better index of agricultural drought. Meteorological droughts do not necessarily coincide with agricultural drought. It means an agricultural drought may exist even though meteorological drought may not and vice versa.

The agricultural drought indices have been mainly based on rainfall deficiency (both amount and distribution) and occurrence of dry spells, evapotranspiration, soil moisture deficit, and water balance. Effect of these factors on crop yield is generally considered as a measure of drought. The indices other than rainfall deficiency, take into account soil moisture budgeting approach in some way or the other. The general form of basic water balance equation is:

$$(P + I) - (Q \pm D + AE) = W \qquad \dots (12)$$

where P = precipitation, mm

I = irrigation water, mm

Q = surface runoff, mm

D = deep drainage below the root zone, mm (opposite sign when there is groundwater table contribution)

AE = actual evapotranspiration, mm

W = chance in soil water storage, mm

During condition of drought, associated with extended rainless period and in the absence of irrigation the terms P, I, Q and D are zero or negligible, thus study of evapotranspiration and soil water content changes become very important for drought analysis. The agricultural drought indices based on various factors are discussed below.

4.2 Based on Rainfall Deficiency and Dry Spells

Deficiency of rainfall has been the principal criteria in defining agricultural droughts. Different limits of rainfall deficiency have been proposed by various workers and organisations to study their impact on agricultural drought (Malik, 1963 , Malik & Govindaswamy, 1962-63, NCA, 1976). It has been defined as an occasion when weekly rainfall in four consecutive weeks is half of the normal or less (normal weekly rainfall being 5 mm or more) in the period from middle of May to middle of October or six such consecutive weeks during the rest of the year (NCA,1976). Khambete and Biswas(164) inferred from their drought study over the dry farming tract of Maharashtra that agricultural drought occurs when there is a rainfall deficiency of less than 18 mm per week during the months June to October. Sastry and Chakravarty (1984) defined drought in consideration of crop growth stages and considered a day having less than 6 mm of rainfall as a dry day. If a dry week of seven such sequential dry days occurs ≥ 4 times during vegetative, ≥ 2 times in tasselling, ≥ 4 times in grain filling and maturity phases of maize crop or ≥ 10 times during sowing to harvest of this crop, it is called an agricultural drought. Chowdhary et al. (1979), Victor and Sastry (1979), Ramana Rao et al (1976) and many others have tried the probability analysis of occurrence of 'dry spells' of short and long duration (ranging from few days to 2/3 weeks) for determining drought proneness and crop planning generally using Markov-Chain model. The probability of rainfall occurrence at various probability levels on weekly basis has been also attempted by many to study agricultural drought using Weibull plotting position formula (Rao & Phulari, 1984; Sikka & Soni, 1987 and others).

4.3 Based on Rainfall and Evapotranspiration

Since rainfall governs the water supply and evapotranspiration represents the crop water demand, both of these hydrologic variables have been used to define index of agricultural drought by various workers in many ways.

4.3.1 Climatic crop growth indices (CCGI)

In order to replace crude rainfall indices, Presscott (1958) advanced this index in Australia considering the fact that water need of growing plants is dependant on climatic conditions vis-a-vis complex association between soil and vegetation. This index utilises plant soil rainfall interaction concept in any indirect way and uses different ratios of pan evaporation to classify intensity of droughts. The CCGI is given as:

$$CCGI = P/(E_w)^{0.75} \qquad ,,, (13)$$

where P = rainfall, and E_w = measured or calculated evaporation rate

Das et al. (1971) modified this equation using potential evapotranspiration (PE) estimates instead of E_w and gave the following equation:

$$CCGI = P/(0.769\ PE) \qquad ... (14)$$

On the basis of equivalent rainfall amounts to these limiting CCGI values, four drought classes were defined as given below:

P_i	=	Nil Severely	$\upuparrows$ $\downdownarrows$	growth restricted growth	= 0.4 (0.769PE) = 0.307PE, influential rainfall required for a break of season
P_d	=	Restricted	$\downdownarrows$	growth	= 0.8(0.769 PE) = 0.615PE, the minimum rainfall for satisfactory growth of drought tolerant crop
P_h	=	Satisfactory	$\downdownarrows$	growth	= 1.2 (0.769 PE) = 0.992 PE, minimum raianfall for satisfactory growth of average crops & pastures.
P_a	=	abundant	$\downdownarrows$	growth	= 1.6 (0.769 PE) = 1.220 PE, the rainfall creating conditions for good growth for most crops, plants and dense growth.
P_{a2}	=	Surplus	$\downdownarrows$	growth	= 2.4 (0.769 PE) = 1.844 PE, the rainfall for abundant and dense growth of paddy.

Classification of drought is given below:

Moderate drought = when $P_a/P_n > 1$

Large drought = when $P_h/P_n > 1$

Severe drought = when $P_d/P_n > 1$

Disastrous drought= when $P_i/P_n > 1$

where P_n is the normal rainfall.

Das (1980) classified the country into various drought intensity classes using this concept for advocating necessary soil conservation measures. They estimated that nearly 80% of the country is subject to droughts. While only 6% to disastrous droughts, 36% to severe, 14% to large and 24% to moderate droughts. Like other approaches reviewed this delineation or the basis used also do not provide the probability of recurrence of a particular type of drought in any year. The annual delineations of drought affected areas do not offer true picture as seasonal variations and long dry spells in the rainy seasons are not detectable. The monthly values may be more useful in identifying the area and planning the control measures. However, it appears that the drought intensities are slightly over estimated in certain cases. The Penman method was used for computation of PE. The valaues obtained by using CCGI values need further refinement.

4.3.2 Ratio of rainfall to PE

This ratio has been used for obtaining various moisture condition classes in India (IMD) and abroad (FAO). Hargreaves (1974) estimated monthly rainfall at 75% probability level and used ratio of this to the average monthly PE for classification of agro climate of Brazil and designated this ratio as 'Moisture Availability Index (MAI). Biswas and Nayar (1984) applied MAI (defined as ratio of probabilistic rainfall of a week to PE) for agricultural drought studies. They considered poeriod of MAI $\geq$ 0.3 as the crop growing period and the mid season water stress period i.e. when MAI $\leq$ 0.3, from 50% probability level was used to map drought prone areas both in space and time. Severity of drought has been classified by the number of water stress periods as well as their durations. This method has been used to identify the core of drought prone area in dry farming tracts.

The percentage disparities of actual raianfall from the normal requirement of amman paddy crop for each month and for the season were calculated and classified in five categories of drought of different intensities with respect to this crop in West Bengal by Misra (1983) as given below:

Categories of droughts	Percentage departure of rainfall from the normal requirement of crop
Very slight drought	Less than 10
Slight drought	10 - 20
Moderate drought	21 - 40
Severe drought	41 - 60
Disastrous drought	More than 60

4.4 Rainfall & Crop Production

In a recent study, Jha (1986) proposed two parameters 'effective deficiency (ED)' and effective deficiency with extreme conditions duly represented to study agricultural drought and illustrated the use of this approach using long term raianfall and crop production data of Palamu district, Bihar. The parameters using long term input sequences, rainfall in this case, have been compared with equivalent crop production (CP_e) to present drought situation.

As the crop production of our country has been continuously increasing during analysed years because of government encouragement and other reasons it was found necessary to reduce this yearly crop production to a suitable base year i.e. 1980-81. This was termed equivalent crop production (CP_e). This equation for CP_e proposed by him is as follows:

$$CP_e = \frac{CP_{cb}}{CP_c} \times CP \text{ (Tonnes)} \qquad \ldots (15)$$

CP_{cb} = equivalent crop production for base year

= 85894.8 + 2402.76 x

x = n = 17th yr. for this case

CP_c = Y for x = 1 to n, years for which data are analysed

n = 17 for this case

coefficient of correlation = 0.9295

Effective Deficiency (ED)

$$ED = R \sum_{i=1}^{n} W_i * K_i \qquad \ldots (16)$$

W_i = weight to be assigned to ith period

$$K_i = |(V_i - \bar{V}_i)| \quad \text{if } (V_i - V_i) < 0$$

$$= 0 \quad \text{if } (V_i - \bar{V}_i) \geq 0$$

V_i = variation between the input sequence at period i and the required input at period i

$\bar{V}_i$ = the average of the variations in the ith period as obtained from the historical data

$$R_r = \frac{\text{The normal annual condition of the inpupt sequence}}{\text{The actual input in the same year}}$$

Effective deficiency with extreme conditions (ED_e)

$$ED_e = R_r * [\sum_{i=1}^{n} (W_i * K_i)^2]^{\frac{1}{2}} \quad \ldots (17)$$

K_i, W_i & R_r have same meaning as in above expression

Crop production is greatly influenced by water availability in critical growth period. So different weight factor needs to be assigned to each period for different crop to take into consideration the importance that period have for a particular crop

Average weightage for jth month

$$W_i = \frac{\sum_{i=1}^{n} W_{ij} \times A_i}{\sum_{i=1}^{n} A_i} \quad \ldots (18)$$

W_{ij} = weightage worked out for ith crop in jth month. This is assigned values from 1 to zero for a crop taking into account its growth stage.

A_i = area under ith crop

n = number of crops

Thus, ED & ED_e are computed for each year.

The plots between CP_e and ED & CD_e and ED_e on this basis follow a smooth curve. It is suggested that these two parameters ED & ED_e can be used to represent drought condition .

4.5 Based on Water Balance Method

Water balance computations find a great place in drought studies by providing an estimate of the moisture availability to the crop over time and space. The knowledge of probable moisture deficiency (i.e. the extent to which AE falls short of the PE) helps in identifying the onset of drought, its severity and planning water management schemes to obviate the effect of drought. In this direction, aridity index of Thornthwaite and index of moisture adequacy (IMA) have been used with different threshold values for different crops & regions and also on seasonal and weekly basis. In fact both aridity index and IMA are related to each other. But these have been used separately by researchers according to their convenience.

4.5.1 Aridity index for agricultural drought

The definition of I_a has been already presented in chapter 3.0. Chowdhary et al. (1977), Appa Rao (1983) and few others used weekly aridity anomalies using Thornthwaite & Mather (1955) water balance model to study the incidence, spread, intensity and cessation of agricultural droughts on the basis of following drought intensity classification cirteria.

Drought intensity	Aridity anomaly
Mild	25
Moderate	26 - 50
Severe	More than 50

The aridity anomalies maps are prepared by IMD on weekly b[illegible] for the country to identify & monitor drought on a regi[illegible] scale as a useful tool to farmers and planners. In a study using five day water budgets, the droughts were classified as moderate and severe when $PE/2 > AE > PE/4$ and $AE < PE/4$ respectively (Krishnan & Rao, 1979).

But weekly aridity anomalies criteria is more prevalent.

4.5.2 Index of moisture adequcy (IMA)

The ratio of actual to potential evapotranspiration (AE/PE) also known as the index of moisture adequacy (IMA) indicates the rate at which moisture is available to the crop compared to its water demand. Subrahmanyam et al. (1963), Subramaniam and Sastri (1979), Sastri et al . (1984), Patel et al. (1986) and others have employed this criteria using Thornthwaite and Mather (1955) water balance approach to study agricultural droughts in India. Subrahmanyam et al. (1963) concluded that most of the agricultural crops in India do not seem to have favourable conditions for development below 40% value of IMA (i.e. AE/PE 0.4 which corresponds to aridity index of 60%). A value in the range of 60-100% of IMA is required for efficient growth and development of rice. However, when index falls below 80% the yield gets reduced considerably. Similarly for millets a lower range of 40-60% was suggested. Subramaniam and Sastri (1979) obtained the minimal value of IMA (i.e. above which yield is always higher than the average yield and below which it would be lower than the average) for pearl millet, sorghum and finger millets for Andhra Pradesh in the range of 52 to 58%.

The minimal value of IMA (%) below which the yields are less than the average and above which the yields are more than normal for four stations of Rajasthan for three rainfed crops i.e., bajra, jowar and kharif pulses and for two stations of Rayalaseema for three crops viz., jowar, bajra and groundnut are shown in figure 2. The minimal required value of the index for different stations of the regions is tabulated below.

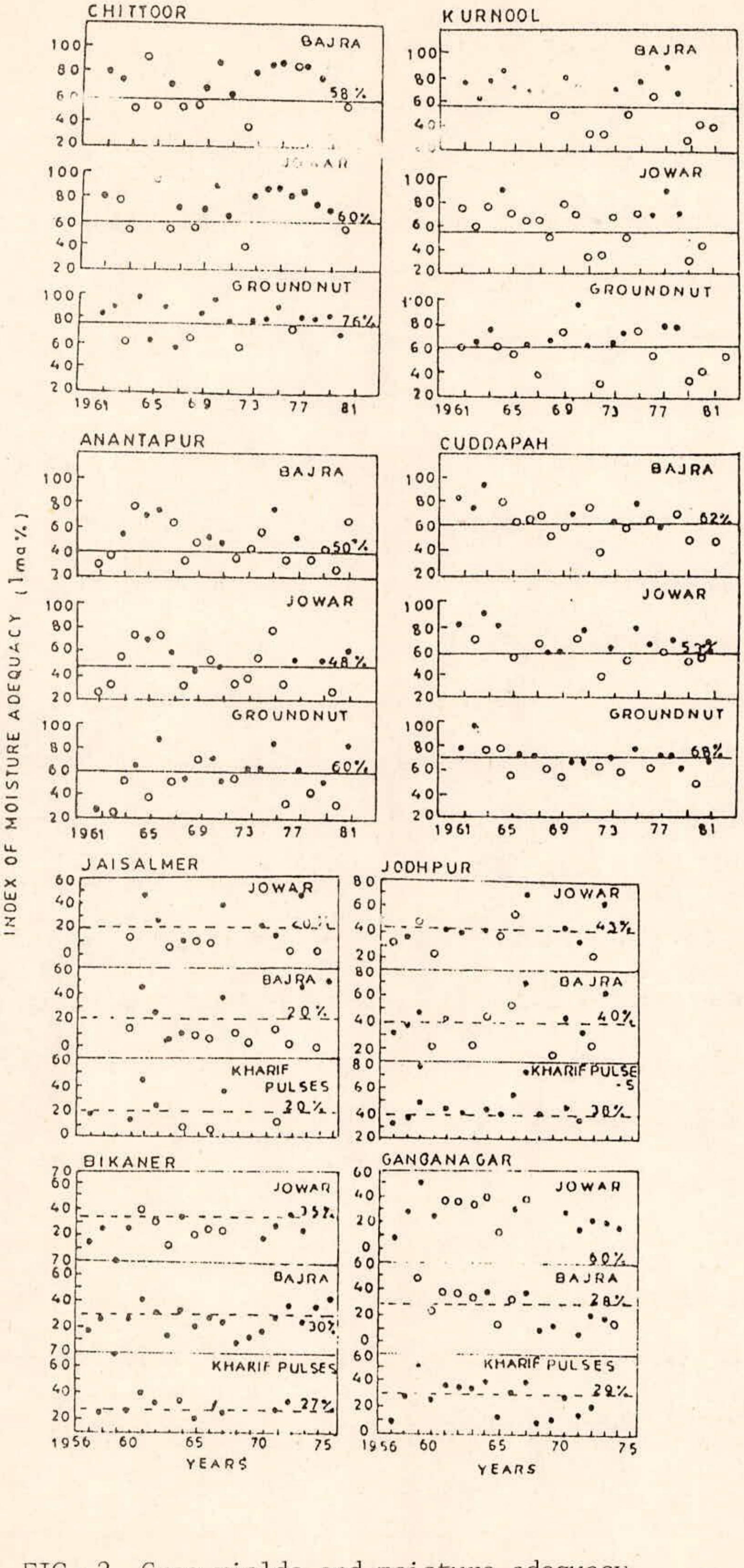

FIG. 2 Crop yields and moisture adequacy

Station	Kharif pulses %	Bajra (Pearl millet) %	Jowar (Sorghum) %	Groundnut %
Rajasthan				
Jaisalmer	20	20	20	-
Jodhpur	38	40	43	-
Bikaner	27	30	35	-
Ganganagar	29	30	35	-
Rayalaseema				
Anantapur	-	50	48	60
Cuddapah	-	62	58	68
Chittoor	-	58	60	76
Kurnool	-	56	54	60

The departure of IMA from the minimal value is considered for classifying the agricultural droughts which will vary from crop to crop and region to region. Such a scheme for classifying the agricultural droughts is arbitrary, but based on some rational thinking. The following classification has been suggested for various regions:

Departure of IMA (%) below the minimal value (Andhra Pradesh)	(Western Rajasthan)	Agricultural drought intensity
Less than 10%	5%	Moderate
10 to 20%	5 - 10%	Large
20 to 30%	10 - 15%	Severe
Greater than 30%	15%	Disastrous

Based on the above scheme, the intensity and frequency of agricultural droughts have been commonly studied in Rayalaseema & Rajasthan.

RamMohan et al.(1984) adopted the following approach for classification of drought intensity based on the standard deviation as it is more representative of meteorological drought.

Nevative departure of IMA from normal	Drought intensity
$< 1/2\ \sigma$	Moderate
$1/2\ \sigma$ to σ	Large
σ to $2\ \sigma$	Severe
$> 2\ \sigma$	Disastrous

Sikka (1986) employed improved water balance approach using Budyko-sellers water balance model to compute AE/PE ratio for agricultural drought studies of Bikaner, Rajasthan on seasonal basis i.e. for Kharif season. The criteria used in this study for drought classification has yielded good results when compared with recorded drought years available in the literature.

AE/PE ratio of Kharif season (June - September)	Drought intensity
0.20 to < 0.30	Moderate
0.10 to < 0.20	Severe
< 0.10	Disastrous

The usual onset of effective monsoon is in the month of July and the main Kharif cropping season is also from end of June to September. The pearl millet crop has maturity period of 90-100 days. Therefore, while considering the values of AE/PE for the season (June-September) which is little longer than the actual growing season, the values of AE/PE below 0.30 have been considered reasonable for drought initiation . The values of AE/PE below 0.40 have been otherwise normally considered by investigators for active growing period.

The seasonal values of IMA may not be as accurate in analysing agricultural drought (e.g. Kharif) as the IMA values at different crop growth stages because different growth stages have varying vulnerability to moisture stress. Therefore, the IMA values corresponding to different growth stages when considered produce better estimates of drought. In this direction efforts have been made by Ramana Rao et al. (1982), Sastri et al. (1982), Ramakrishna (1986) & Patel et al. (1986) to suggest optimum values of IMA (i.e. AE/PE) during different growth stages of different crops in Rajasthan & Madhya Pradesh for crops like pearl millet, soyabean, rice, black gram etc. The optimal required values of AE/PE during seedling, vegetative, reproduction and maturity stages of dry land crop in general were given as 0.25, 0.50, 0.75 and 0.25 respectively by Raman Rao et al. (1979), based on the knowledge of crop water requirements. The duration of different growth stages of the crops and the required optimal values of AE/PE for different stages extracted from Sastri et al. (1982) and Patel et al. (1986) are presented in Table 2. In general the maturity stage may not be that important as water stress during this stage is not that detrimental to crop yield. A generalised classification of agricultural droughts based on AE/PE values during different growth stages with no specification of any crop suggested by Ramana Rao et al. (1981) is as below:

AE/PE (%) during different growth stages	Drought intensity
76 to 100	No drought
51 to 75	Mild drought
26 to 50	Moderate drought
25 orless	Severe drought

Sastri et al. (1982) have presented a scheme of drought coding for pearl millet which is the major rainfed crop in the Indian arid zone considering AE/PE ratio at seedling, vegetative and reproductive stages

TABLE - 2

Required AE/PE (%) during different growth stages of various crops

Crops	Station	Seeding stage		Vegetative state		Reproductive stage		Maturity state	
		Period (weeks)	AE/PE	Period (weeks)	AE/PE	Period (weeks)	AE/PE	Period (weeks)	AE/PE
Pearl millet	Sikar	3	69	4	61	4	56	3	-
	Jodhpur	3	60	4	44	4	44	3	-
	Nagapur	3	51	4	36	4	32	3	-
	Barmer	3	51	4	39	4	27	3	-
	Jailsamer	3	21	4	16	4	9	3	-
Rice	Raipur	3	75	5	100	4	100	2	50
Soybean	-do-	3	50	4	75	4	50	3	50
Blackgram	-do-	2	50	4	60	4	50	2	40
Groundnut	-do-	3	50	5	75	5	75	3	50
Kodomillet	-do-	3	30	5	50	3	50	3	30

of crop growth. Patel et al . (1986) studied the agricultural drought pattern for 5 crops (as in table 2) chosen during the years 1981 & 1982 at Raipur. Figure 3 depicts the pattern of agricultural drought while considering various growth stages. It could be seen from the figure 3 that occurrence of drought spell during vegetative phase is more or less a common feature in the area. Rice and groundnut crops appear to be more vulnerable to drought as moisture stress has prevailed in vegetative and reproductive phases which are detrimental to crop yields.

4.6 Crop Moisture Index

Palmer (1968) modified PDSI to better reflect agricultural drought conditions and developed crop moisture index to prepare weekly crop moisture index map of USA for the growing season as a measure of agricultural drought. The Crop Moisture Index (CMI) is designed to provide information in response to broad scale general questions rather than the localised questions. In its simple term, it considers agricultural drought as an evapotranspiration deficit. The final crop moisture Index is the algebric sum of the two numbers, namely the evapotranspiration anomaly index and the wetness index. The CMI stands at or near zero at the start of growing season, remains near zero so long as the crop moisture supply and the weather are near normal, and returns to near zero at the end of growing season . Negative values of CMI always mean that evapotranspiration has been abnormally deficient. CMI provides short term (Upto about 4 weeks) abnormal dryness or wetness affecting agriculture, responds rapidly, changes considerably from week to week and indicates normal conditions at the beginning and ending of the growing season. It is applicable only for measuring short term, week to week status of dryness or wetness affecting warm season crops. It may not be applicable to shallow rooted crops which

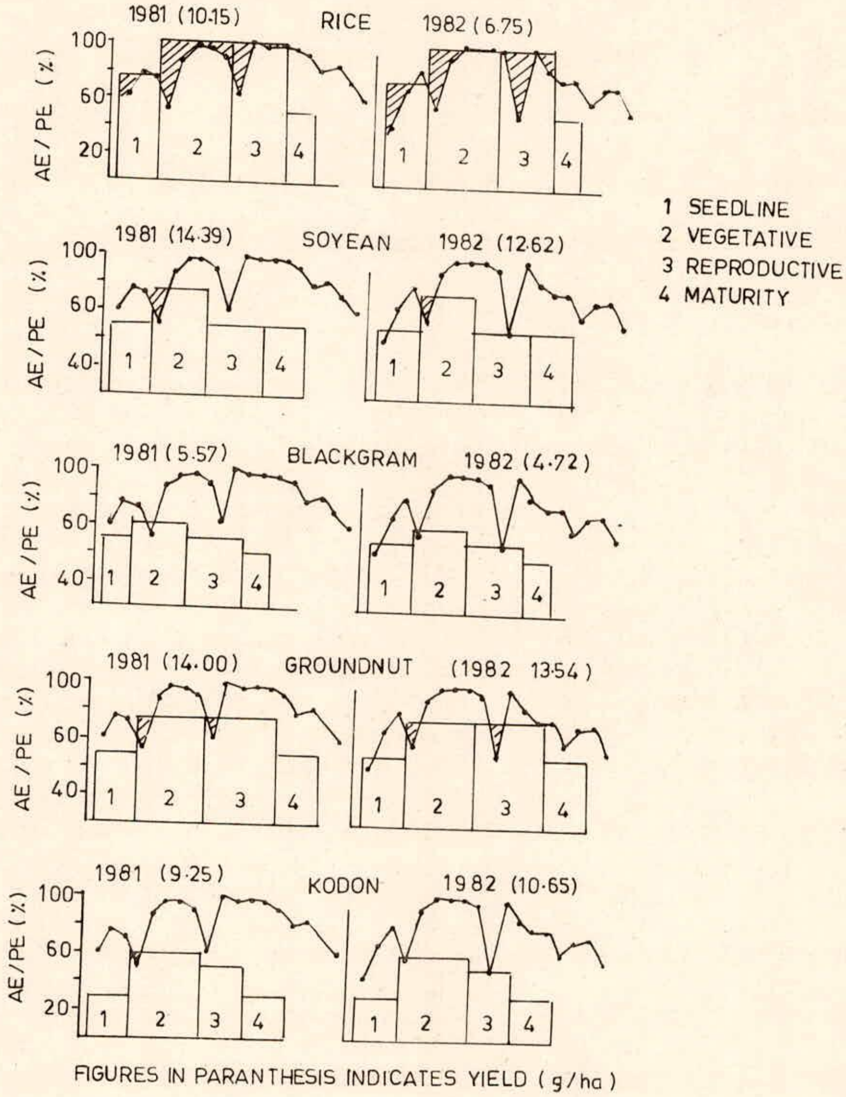

FIG.3 Agricultural drought pattern for 5 crops

are not able to extract soil moisture from a 5-ft soil profile, or for cool season crops growing when temperature are averaging below 55^{O}F. It is not indicative of long term drought or hydrological drought. A relationship between PDI and CMI is also depicted in Figure 4 for growing season which indicates that during weeks 14th through 21st PDI shows moderate to severe drought whereas the positive values of CMI during this period indicate a wet status of soil moisture for crops which explains the usefulness of CMI for short term agriculturala drought only. While interpreting the effects on crops and native vegetation, an account of the stage of growth as well as the status and trend of moisture conditions must also be considered

The studies conducted by Bishion (1984) at Hisar, indicate that the palmer crop moisture index failed to explain the behaviour of crop conditions and analysis of agricultural droughts under rainfed crops. A new crop moisture index developed by him is reported to have explained the crop conditions in accordance with results obtained from experimental plots under dry land agriculture. The agricultural drought has been classified as under based on the crop moisture index values during the growing season of the crop:

C M I	Category of agricultural drought
0 - 0.33	Extremely dry
0.34- 0.75	Dry
0.76- 1.00	Semi-dry
1.01- 2.00	Normal
2.01- 3.00	Moist
3.01- 4.00	Wet
> 4.01	Extremely wet

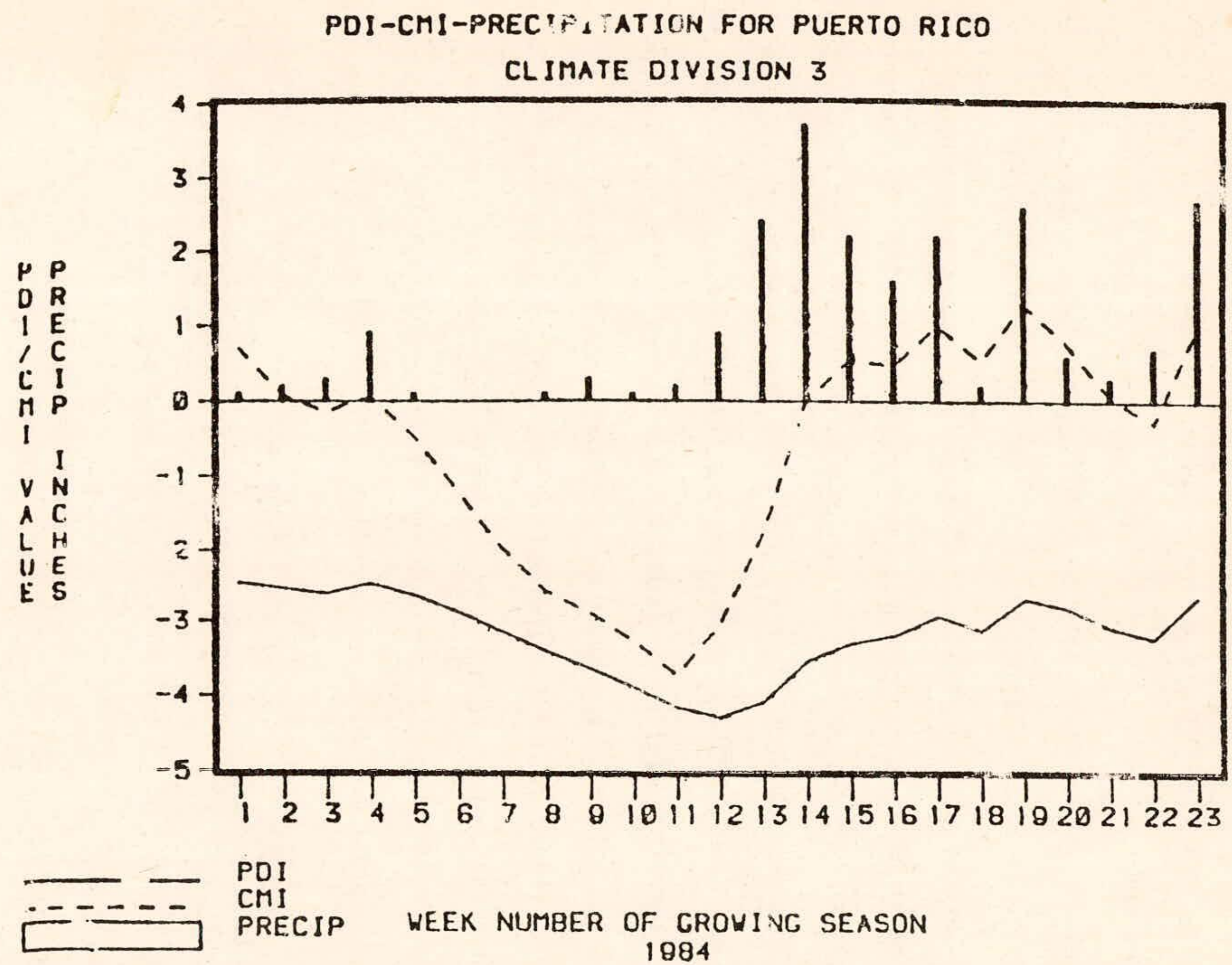

FIG.4 Comparison of PD1 - CM1 - Precipitation index for Puerto Rico (Climat Division),USA

4.7 Based on Soil Moisture

Soil moisture is one of the important components of land phase of hydrologic cycle from where plants extract moisture for their evapotrans-pirational needs. Soil moiosture deficit (i.e. the difference between field capacity and actual or current soil moisture) beyond a certain limit adversely affects plant growth and causes wilting. This results in declined agricultural production which is normally taken as a measure of drought. It is observed that the crop would normally sustain permanent injury when soil moisture falls below permanent wilting point and this may lead to situation of severe or disastrous drought. Therefore, availability of useful soil moisture to the vegetation appears to be a better index of agricultural drought. Soil moisture status also effects infiltration and surface runoff.

Van Bavel (1953) suggested the definition of drought on the basis of soil moisture conditions and resultant plant behaviour, rather than on some direct interpretation of the rainfall record. A drought day was defined as a 24 hour period (starting at the time of the day at which the precipitation of the previous day was recorded) in which the soil moisture stress exceed a limit which, on the basis of experimental evidence, may be taken as a point at which the productive processes of the crop are appreciably decreased. On this basis, number of drought days for each season were computed. It has been observed that by increasing the moisture storage capacity of the soil, the number of drought days could be reduced significantly. Wilhite and Glantz(1985) quoted the studies done by Kulik in 1960 which represented drought intensity as the difference between plant water demand and available soil water. It was reported that the upper 0.2 m of soil was critical to plant grwoth because of nutrient supplies, root activity and activities of micro organisms.

4.7.1 Soil water models for drought

A multitude of soil moisture accounting models have been developed by several investigators (Holmes and Robertson, 1959; Baier and Robertson, 1966; Saxton et al. 1974; Thornthwaite and Mather, 1955; Smart, 1983 & Jain & Murty, 1985) but less attention has been paid to application of these models for drought analysis and management. Holmes and Robertson (1959) developed the modulated soil moisture model which was improvement of their earlier single layer soil moisture model. Baier and Robertson (1966) improved these models with the development of a versatile soil moisture budget model. A more comprehensive soil moisture simulation models have been developed by Saxton et al. (1974) and others for agricultural and hydrological studies.

Some of the investigators have tried to use soil moisture models in drought related stujdies (Cordery, 1981; Owtadolajam, 1982; Smart, 1983; Khalili, 1984; Sikka & Mishra 1986 and others). Owtadolajam(1982) and Khalili (1984) employed a soil water budgeting model to simulate soil moisture stress (i.e. the difference between potential and actual evapotranspiration) on forage and rangeland production in semi-arid and arid areas of USA. Single layer soil model applying the concept of Budyko-Selleers water balance approach was used. The general form of regression model of soil moisture stress to yield was:

$$\text{Yield} = a_o + \text{Sum}\ (a_i \times \text{Stress}_i) \qquad \ldots (19)$$

Equation (19) represents annual production as a linear function of the individual stresses from various months or seasons. The coefficients

a_o and a_i indicate the relative influence of various monthly or seasonal stresses on herbage production. Annual grass production was regressed against soil moisture stress.

Smart (1983) used a conceptual daily soil moisture accounting model run with daily rainfall and evaporation inputs to simulate soil moisture levels for the top 10 cm soil under irrigated and unirrigated conditions for drought studies in rye grass pasture at New Zealand. The simulated soil moisture values were used to illustrate statistical procedures (theory of runs) for drought frequency, duration and severity. Soil moisture content (% by weight) below which severity of drought was defined, included 10, 12, 14, 16, 18 and 20% as illustrated in figure 5. The model assumes that if rainfall is less than soil moisture deficit, all the rain-fall would go to recharge the soil which may not be true when intensity of rainfall is greater than infiltration rate of soil and in such case surface runoff will take place. The model (flow chart as shown in Figure 6 also do not differentiate between surface runoff and percolation losses below the root zone.

Sikka and Mishra (1986) suggested use of the following soil water balance equation to determine soil moisture available for plant growth in the root zone, assuming that the affect of water table is not there.

$$Q_{(t+1)} = Q_{(t)} + P - R - S - AE \qquad \ldots (20)$$

where,

$Q_{(t)}$ = soil moisture at beginning of t^{th} day in mm,

$Q_{(t+1)}$ = soil moisture at the end of t^{th} day in mm,

P = precipitation during t^{th} day in mm,

R = surface runoff during t^{th} day in mm,

S = deep percolation below root zone in mm, and

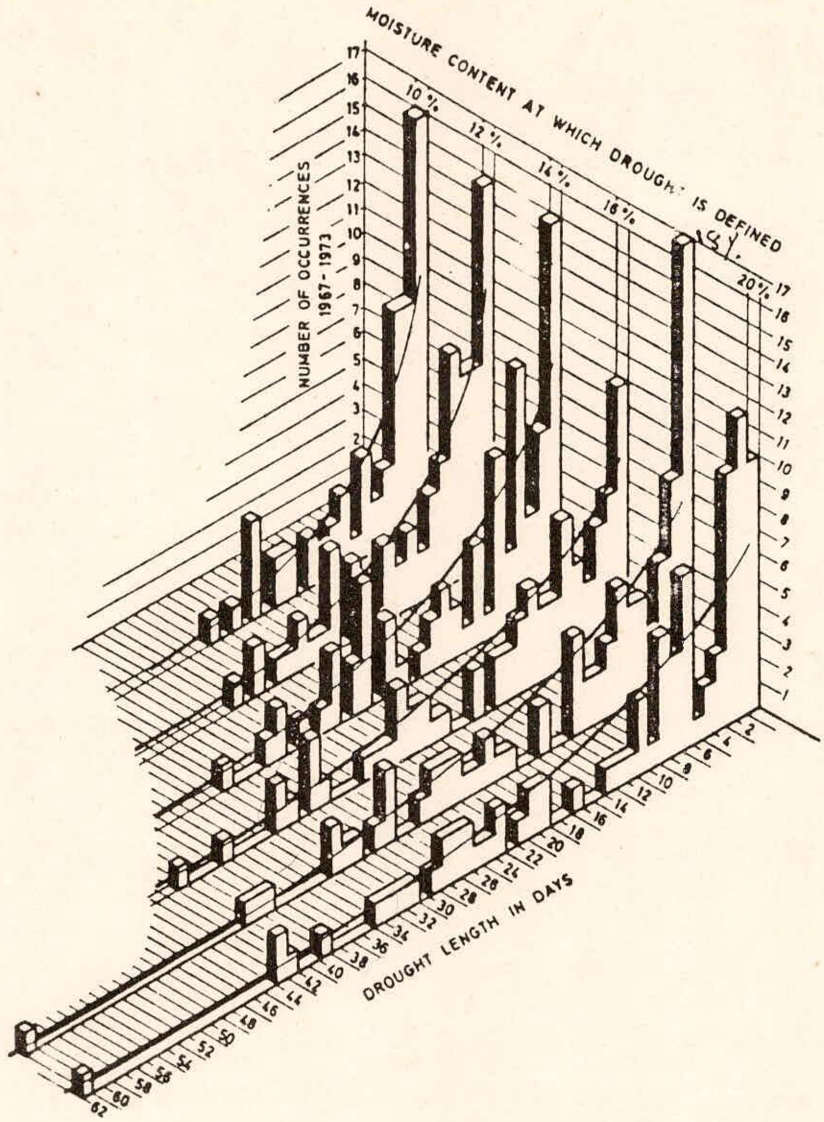

FIG.5 Frequency, duration and severity of droughts
0 - 100 mm below pasture (1967-73)

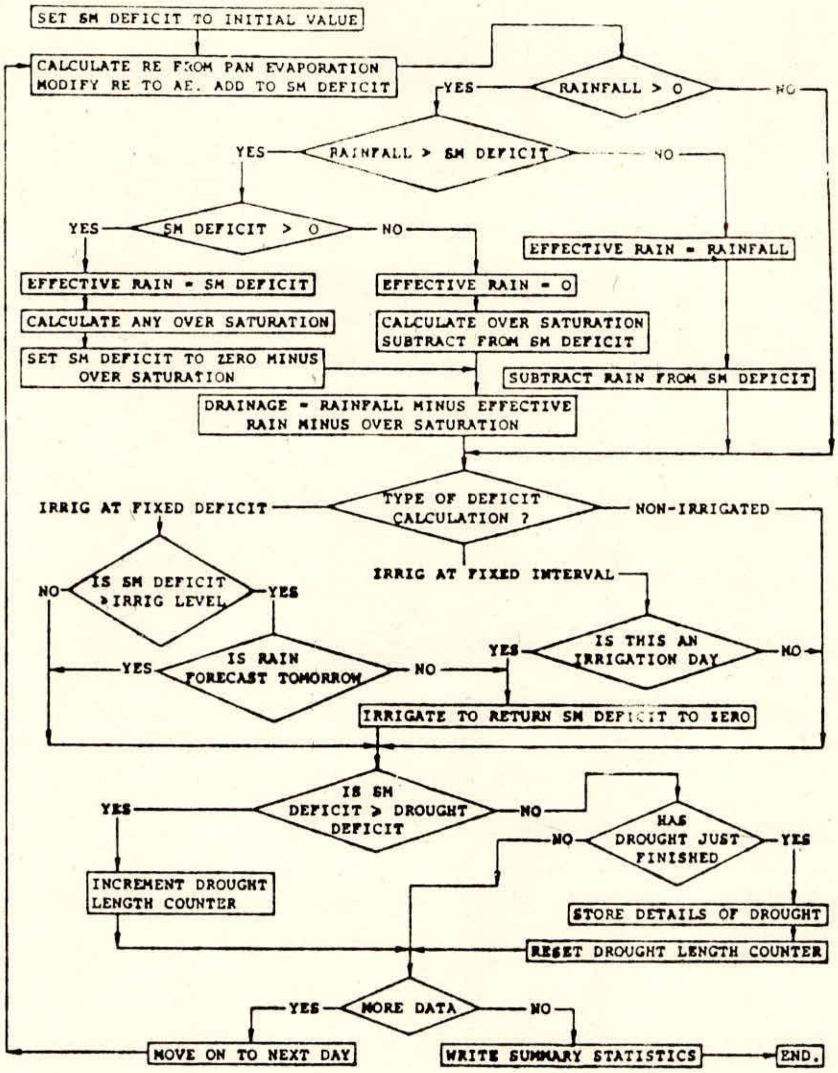

FIG.6 Flow chart of algorithm for estimation of daily soil moisture

AE = actual evapotranspiration during t^{th} day in mm.

AE is proposed to be evaluated using following linear relationship.

$$AE_{(t)} = PE_{(t)} \frac{(AW_t)}{(AWC_t)} \qquad \ldots (21)$$

where

$AE_{(t)}$ & $PE_{(t)}$ = actual & potential evapotranspiration of t^{th} day in mm,

AW_t = available soil moisture on t^{th} day in mm, and

AWC_t = available soil water capacity or water holding capacity on t^{th} day in mm.

A two layer soil water model (i.e. upper and lower layer depending upon soil characteristics) has been suggested with linear root growth model for withdrawal of soil moisture through evapotranspiration. The root zone is assumed to linearly extend from depth (Y_o) at time (t_o) i.e. time of plant emergence and to reach its full extension to depth (Ymax) at time of full canopy development.

Daily infiltration is computed as difference in the average rainfall of watershed and computed or observed wateshed runoff expressed in depth units.

$$I = P - R \qquad \ldots (22)$$

where,

I = Daily infiltration, mm

P = Daily rainfall, mm

R = Daily runoff from watershed, mm

Surface runoff in small watesheds can be estimated by the standard soil conservation service (SCS) curve number technique using easily available rainfall and watershed data.

In this theoretical study, the following criteria has been proposed using soil water deficit - SWD (different of field capacity and current soil moisture) values to define a day as a drought day with different severity levels.

If, SWD/AWC	=	0.7 to 0.8	Moderate drought
SWD/AWC	=	0.8 to 0.9	Severe drought
SWD/AWC		$>$ 0.9	Disastrous drought

These are the suggested tentative limits to define various drought severity levels and would depend on the crop and soil type. The number of drought days during the growing season can be determined using this approach and drought days could be classified in different severity groups.

It is also suggested that an appropriate weightage factor or yield susceptibility factor should be introduced to take care of critical crop growth stages. An approach to incorporate this aspect is suggested as below:

Daily Drought Index (DDI) = SWD x weightage factor or yield susceptibility factor ... (23)

Depending upon the sensitivity of the growth stage, appropriate weightage factors have to be assigned.

4.8 Integrated Scheme for Classification of Droughts

A methodology was proposed to work out an integrated scheme for drought classification in which the overall effect of the meteorological, climatological and agricultural aspects of drought were considered in a given region (Indian arid zone) for examining the intensity and extent of drought (Ramana Rao et al., 1982). Equal weightage were provided to agricultural droughts and drought conditions based on departures from rainfall and aridity index. These variations during different phenophases of crop growth were considered while defining the intensity of drought in its totality. The coding of meteorological, climatological and agricultural drought intensities were done which are as below:

Intensity of drought	Met.drought	Clim drought	Agril. drought		
			Seeding	Vegetative	Reproductive
No drought	M_o	C_o	S_o	V_o	R_o
Mild drought	M_1	C_1	S_1	V_1	R_1
Moderate drought	M_2	C_2	S_2	V_2	R_2
Severe drought	M_3	C_3	S_3	V_3	R_3

According to this coding, a region having no drought on the basis of annual rainfall departures (M_o), mild drought on the basis of departure from aridity index (C_1) and no agricultural drought during seeding, vegetative phases followed by severe drought during reproductive phase can be expressed to have a drought code as $M_o\ C_1\ (S_o\ V_o\ R_3)$. The final drought code can be written as $M_o\ C_1\ A_1$, where A_1 represents mild agricultural drought.

The integrated code for classification of drought to project the combined effect of meteorological, climatological and agricultural droughts was obtained by summing up the numericals suffixed to the three categories of droughts giving all of them equal weightage and magnitude of drought was classified as below:

Scale	Drought Intensity	Code
0	No drought	D_o
1 - 3	Mild drought	D_1
4 - 6	Moderate drought	D_2
7 - 9	Severe drought	D_3

Thus, the classification $M\ C_1\ A_1$ becomes D_1 indicating situation of mild drought. The analysis of 1979 & 1980 drought was done for Western Rajasthan using this scheme. The drought code for the year 1979 at Jodhpur was obtained as $M_o\ C_o\ (S_1\ V_1\ R_2)$ or $M_o\ C_o\ A_1$, thus resulting in mild drought.

The criteria for fixing agricultural drought intensity based on stresses during their growth stages for pearlmillet crop is explained by Ramakrishna (1986). There was no deficit in rainfall and departure from aridity index at Jodhpur, and only mild agricultural drought conditions prevailed affecting the productivity of pearlmillet only. Moreover, the Kharif pulses and grasslands escaped drought conditions to a considerable extent. Therefore, classification of overall impact of drought condtions at Jodhpur during the year 1979 as mild based on the above criterion was reported to be well justified and nearer to actual conditions experienced in the region.

The integrated scheme as explained above gives equal weightage to all the there factors irrespective of their time distribution and dependance for water demand. The scheme could be improved by assigning due weightage to different factors rather than assigning equal weightage.

5.0 HYDROLOGICAL DROUGHT INDICES

5.1 General

Hydrological drought indices are concerned with the effects of rainfall deficiencies on hydrological components such as surface water, ground water and soil moisture. In the direction of hydrological drought, the indices in the form of numerical numbers indicative of drought occurrence are not many. Rather more complex statistical and stochastic hydrologic models are found in the literature. The hydrological drought has been defined by various researchers. Whipple (1966) defined a drought year as one in which the aggregate runoff is less than the long term average runoff. Yevjevich (1967) defined the term hydrologic drought as "the deficiency in water supply or deficiency in precipitation, effective precipitation, runoff or accumulated water in various storage capacities". Linsley et al. (1975) defined hydrologic drought as a "period during which stream flows are inadequate to supply established uses under a given water management system".

Six types of drought have been distinguished based upon variations in the duration, season of year, or severity by Beran and Rodier (1985) mainly relating to agricultural and irrigational needs.

1. A three week to three month runoff deficit during the period of germination and plant growth. This could be catastrophic for farming that is dependent upon irrigation drawn directly from the river without the support of reservoirs.
2. A minimum discharge significantly lower or more prolonged than the normal minimum but not necessarily advanced much in its position relative to the growing season. Because the germination period is not affected this type of drought is of less consequence to

agriculture.

3 A significant deficit in the total annual runoff. This affects hydropower production and irrigation from large reservoirs.

4. A below normal annual high water level of the river. This may introduce the need for pumping for irrigation. Thie type of drought is related to Type 3- deficit in annual runoff.

5. Drought extending over several consecutive years. Discharge remains below a low threshold or the rivers dry up entirely and remain dry for a very long time.

6. A singificant natural depletion of aquifers. This is difficult to quantify because observation of the true level of the aquifer is disturbed by the over utilization of ground water during the drought.

It is evident that the hydrological variables such as stream flow & reservoir levels, ground water and catchment soil moisture can be used to define hydrological drought and develop suitable drought indices. The runoff or streamflow indices have been generally used to define hydrological drought to a limited extent.

5.2 Based on Surface Water

5.2.1 Runoff indices

The hydrological drought is considered to be in progress when the actual flow in a stream for a selected period of time falls below a certain threshold. However, the number of days and the level of probability that must be exceeded to define a hydrologic drought period is arbitrary. These criteria are specific to individual stream or river basins and the period of intended water use demand in that area. A commonly used simplest index is to compare the depth of precipitation and runoff depth or volume for a given duration i.e. week, fortnight, month or a year, with the long term mean or standard period normal value for the given duration. The numerical value of this index will give the drought severity. This could be classified on the basis of probability also. One such scheme as found in Europe is as below (cited from Beran & Rodier, 1985).

		Exceedance frequency between
Very wet	:	0 and 15%
Wet	:	15 and 35%
Normal	:	35 and 65%
Dry	:	65 and 85%
Very dry	:	85 and 100%

Normally 80 and 100% exceedance frequency is considered in order to develop a regional drought summary based upon a number of flow records.

The Central Water Commission (1982) while studying drought in 99 districts of the country considered hydrological drought as a situation when annual runoff for the year under consideration is less than 75% of the normal annual runoff. If there are 25 such years in the area, the area is termed as drought prone. This runoff reduction ultimately results in lowering of water levels in reservoirs, tanks and streams causing situation of water deficit for the user in the area.

Thornthwaite and Mather (1955) book keeping water balance model has been also used to estimate water surplus/deficit of river basins as a tool to define hydrological drought (Srivastava et al., 1977, Subrahmanyam and Upadhyay, 1983). Shelton (1982) studied the 1977 california drought using Thornthwaite's climatic water balance model by computing cummulative moisture deficiency calculated for the duration of the drought. Stockton (1984) studied the simultaneous occurrence of drought in various regions in the USA using long term streamflow data (1932-80). An empirical definition of hydrological drought was adopted according to which a drought year was defined as any year among the driest 10 years (driest 20%) in a given regional time series from 1932-1980. The analysis was restricted to regions whose streamflow was determined mainly by cool season precipi tation. A time series plot of regions in drought is shown in figure 7. It indicates that only in the year 1977, all the four regions were simulataneously affected by drought.

Although the Palmer drought severity index (PDSI) is basically an index of meteorological drought, but because of its ability to reflect long term moisture, runoff, recharge and evapotranspiration it is used in the USA to get an idea about the long term status of water supplies in acquifers, reservoirs and streams. Therefore, it is sometimes used as a measure of hydrological drought also. George et al. (1973) while studying drought in India using PDSI, indicated that in humid and moist sub-humid areas it may represent hydrological drought.

Riggs (1979) used the recurrence interval of the 30-day annual minimum flow as the seasonal drought index at a gauged site for the unregulated condition. The multi year drought index was based on the draft that could be obtained, given a fixed amount of storage, during a multi-year drought. The procedure for defining the multi year drought index proposed by Riggs is as follows:

1. Plot hydrograph periods from hydrograph
2. Identify drought periods from hydrograph

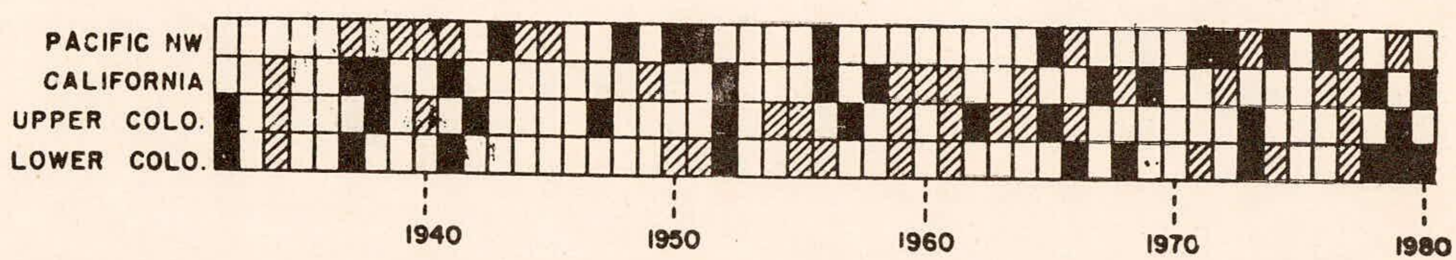

FIG.7 Drought and wet years in four regions of USA

3. Plot a mass curve of annual means encompassing each drought period

4. On each mass curve draw a draft rate line limited by a storage equal to the mean annual flow volume and by a period of deficient flow of 6 years

5. Compute draft rate as a percent of mean flow

6. Compute drought index as the product of 100 minus draft rate and the square root of the deficient period in years

For doing so, define the draft that would have been available during each drought period assuming that reservoir storage equal to the mean annual flow volume were in the basin.

5.2.2 Surface water supply index (SWSI)

The SWSI number is a general indicator of basin wise surface water supply conditions which integrates historical data with current data of reservoir storage, streamflow and precipitation at high elevation into a single index number (Dezman, 1982). It generates monthly numerical values that express the current and future availability of water supplies to meet a multitude of competitive demands with an objective that water supply condition can be assessed to compare drought severity.

The Drought Assessment and Response Plan of Colorado, USA is implemented when SWSI and PDSI values exceed specified thresholds.

A composite reservoir datum, snowpack datum and precipitation datum is found by summing monthly station data. In this fashion anomalies at individual stations are evened out. Frequency analysis is carried out for each component of discharge to find non exceedance probability (PN). As each component is reduced to one scale, comparisons among them becomes simple. Non exceedance probability analysis takes into account dispersion tendency also.

SWSI can be found by using following weighting eqation

$$SWSI = \frac{[(a \times PN_{spor\ SF}) + (b \times PM_{PCP}) + (c \times PN_{RS}) - 50]}{12} \quad \ldots (24)$$

where,

a, b, c - weights for each component, a+b+c =1

S For SP, PCP, RS = stream flow or snowpack, precipitation and reservoir components

for each basin winter & summer a, b & c values are unique

Now drought can be classified on the basis of SWSI values as shown below:

SWSI	Designation
+4	Abundant supply
+2	Near Normal
-1	drought water availability task force activated
-2	Moderate drought
-3	Severe drought
-4	Extreme drought

The weightages a, b & c are based on components impact on water availability of the region. This index is used by Colorado state government. They decide final weightages on the hypothesis that the additive nature of the components cause the SWSI to be normally distributed. The chi-square statistic is used to optimize goodness of fit for trial component weights.

This SWSI index shows drought severity and not duration of drought. This duration will involve gradient component in index. This step will refine the index.

5.3 Based on Catchment Soil Water Deficit

Since soil moisture status of a catchment affects infiltration and runoff, the catchment soil water deficit could also be considered an indicator of hydrological drought. Cordery (1981 & 1983) made use of probabilistic forecasting of soil water deficit (SWD) as a measure of forecasting hydrological drought. A monthly water balance model was developed to estimate soil water deficit (the difference between the actual water storage and the maximum storage that can be sustained i.e. field capacity). Drought was assumed to occur when there is a large value of SWD i.e. soil is very dry. The SWD of -100 mm of water is required to bring the soil to a state of zero deficit. The model structure used for each of the areas with different root zone capacities is shown in the flow chart (Figure 8).

The model was calibrated and applied for the Namoi river at Gunnedah, Australaia. Figure 9 gives the distribution of forecast SWD values obtained from the model. The figure can be used to determine the probability of occurrence of large SWD, if current SWD is known or assumed. For example, if drought was to be defined as occurring when the SWD is larger than the 90th percentile value, that is in the most negative 10 percent of all SWDs observed for that particular month, then for June, drought occurs when the SWD is below - 119 mm. So from Figure 9 it can be seen that if the December SWD is - 80 mm there is very little chance of being in a state of drought at the end of the following June. However, if the December SWD is - 100 mm there is about 22 per cent chance of being in a state of drought at the end of June. The probabilistic forecasting of hydrological drought depending upon SWD values can be made for short durations (3-6 months).

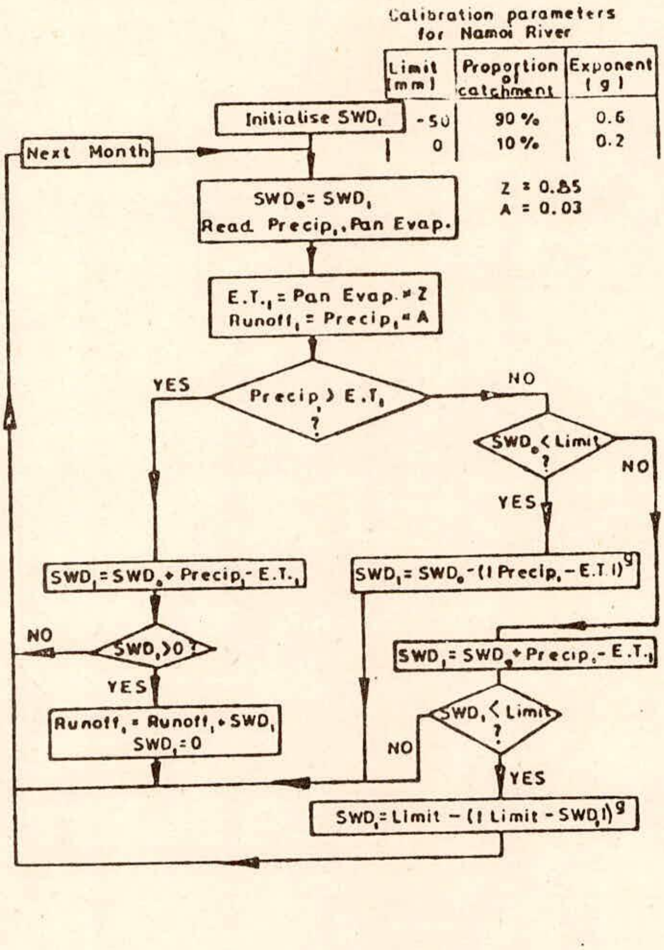

FIG. 8 Flow chart of water balance model

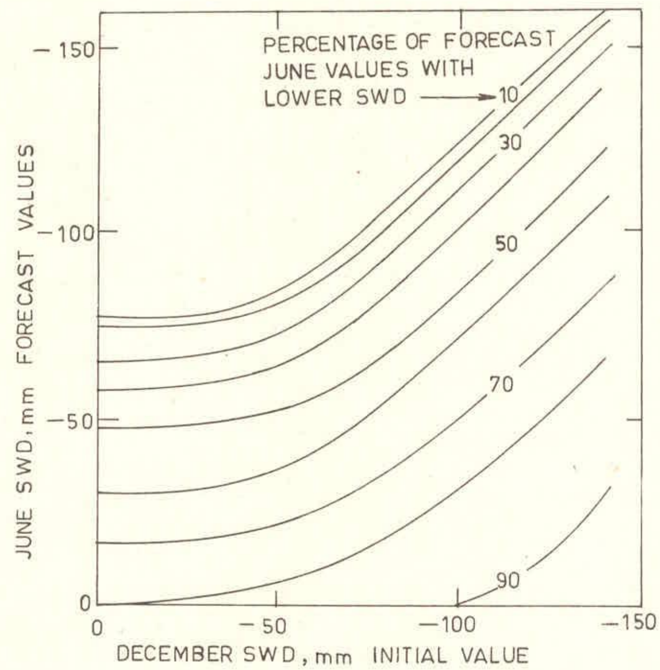

FIG. 9 PROBABILITY OF SWD BEING LOWER THAN SHOWN VALUES IN 6 MONTHS TIME GIVEN CURRENT SWD FOR NAMOI RIVER

5.4 Based on Ground Water Levels

The common approach to study hydrological drought using ground water data is to cosnstruct well hydrographs superimposed with rainfall data using long term historical record. The correct assessment of draft is one of the main problems in judging the impact of drought on ground water. For example, figure 10 persents few typical well hydrographs in Karnataka State depicting the trends of water table over the past few years and this confirms the lowering of water table due to drought(Sikka, 1986b) . Like other drought indices giving some numerical numbers, there appears to be no such attempts made in this direction to develop indices based on groundwater levels.

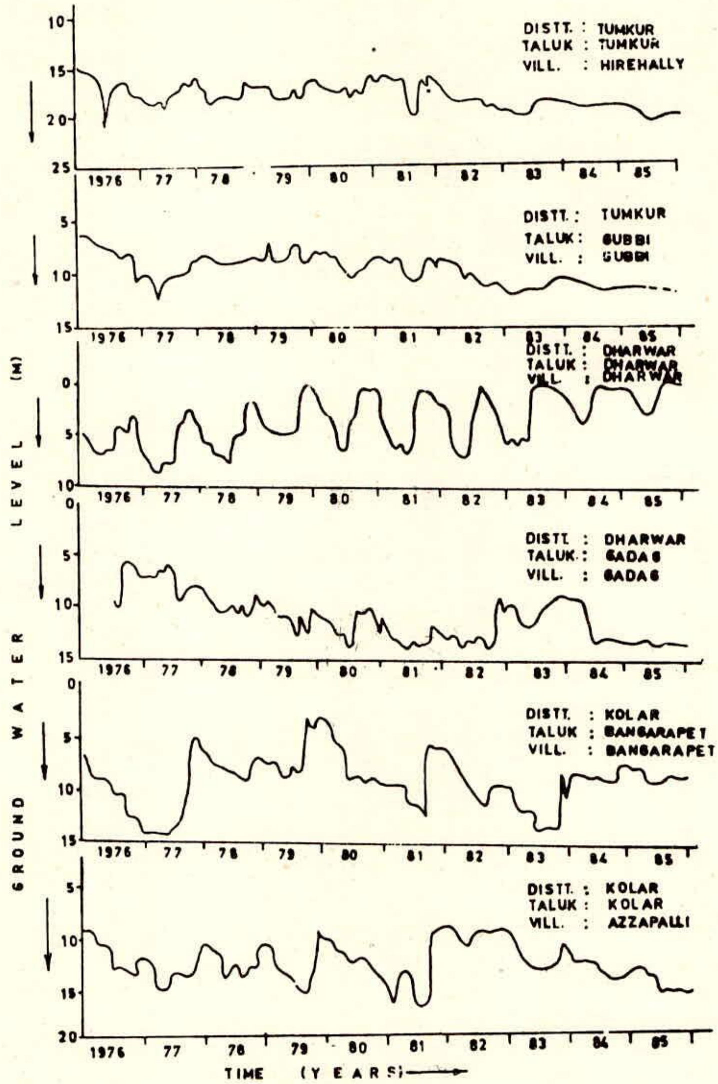

FIG.10 Variation of ground water level (Karnataka) illustrating drought impacts

6.0 DISCUSSION

6.1 A number of drought definitions and indices have been developed varying from simple rainfall indices based on various threshold values to complex indices based on water balance approach and soil moisture models. Most of these indices but for few comprehensive indices appear to be adhoc and work in isolation. They consider either rainfall alone or take some account of soil water storage and loss of water from this storage by evapotranspiration. Rainfall analysis alone has been the main criteria in drought studies, specially in past. The criteria proposed by IMD and also accepted by Irrigation Commission (1972) is most prevalent and commonly practised in the country. This criteria gives a general indication of the excess or deficiency in rainfall when compared to the normal. It does not give any indication about the distribution of rainfall, late on set of monsoon, early withdrawal or interspell duration so vital for crop maturity. The drought indices based on rainfall alone as developed by Herbst (1966) and Bhaleme & Mooley (1981), however, appear to be more rational. The criteria proposed by NCA (1976) also does not take into account the crop water requirement with respect to evapotranspiration losses and the moisture stresses developed in the soil.

6.2 Accumulated rain in itself is not an adequate index of drought condition as it is a relative measure and resulted due to many other interacting variables representing hydrologic process, soil & crop aspects, human and animal factors responsible for water demand variable. It is therefore not sufficient to go by the variability of total rainfall alone but also to analyse and understand spatial and temporal variability in surface water, soil moisture and ground water as well as demand patterns to study drought in a better perspective. Therefore, an overall water availability index could be an index of drought. Thus, water supply minus water demand of drought defining variables eg streamflow, reservoir levels, soil moisture, ground water etc. can be used to describe the drought characteristics for any particular use or interest in water resources.

6.3 Water balance finds a great place in drought studies by providing an estimate of the moisture availability over time and space. The Thornthwaite & Mather (1955) book keeping water balance approach has been extensively used for drought analysis particularly, meteorological and agricultural droughts in the form of aridity & humidity indices and AE/PE ratio (i.e. moisture adequacy index). The aridity index has been applied to agricultural drought studies through aridity anomalies. IMD is regularly issuing weekly aridity maps for drought monitoring. The moisture adequacy index seems to be still better approach particularly if the concept of crop growth stages is incorporated. Since there are limitations in using the Thornthwaite & Mather (1985) approach, improved water balance models need to be used. Most of the commonly used models ignore the details of infiltration process and assume that soil water storage is always replenished provided adequate water is available at the surface. Therefore, improvements in water balance procedures for drought analaysis can be effected by incorporating soil moisture characteristics, two layer soil water models, time variant root zone depth & critical stages of crop growth. The water balance approach for analysis of drought is far better than rainfall approach. Thornthwaite & Mather approach is basically a climatic water balance approach. Hydrologic water balance model including ground water balance need to be used for detailed drought studies. Extensive measurement of soil moisture and actual ET are much needed for water balance studies.

6.4 Another important aspect of drought studies is the level of study i.e. a regional level, local level e.g. district, taluka etc., crop level or a particularl water user's level. Due to different water needs at various levels, there may be drought for a crop or any water use in the given region, but the region as a whole may not be under drought. The occurrence of drought for the region as a whole may have to be based on the overall water deficit. Therefore, integrated drought index must have some scale to define the drought of various levels considering time & use variant threshold values.

Time period consideration is one of the most important factors in selection of appropriate drought indces. Meteorologically, there may be no drought if precipitation on monthly basis is normal, but it may happen to rain too early or too late leaving a dry spell of over 2-3 weeks which may cause the situation of agricultural drought. It could be still severe if it coincides with critical crop growth stages. Therefore, time interval in agricultural drought studies should be short i.e. weekly or daily keeping view of critical crop growth stages. Normally longer time intervals e.g. yearly, seasonal or monthly are used in meteorological or hydrological drought studies. Even the short time intervals like 10 days, 15 days etc. are preferred some times in hydrological drought studies particularly during the period of water scarcity when supplies for domestic water needs, cattle needs etc. get adversely affected.

6.5 Operational definitions of drought attempt to identify the onset, severity and termination of drought and could also be used to calculate the probabilities of droughts. An operational drought index specially for agricultural droughts could be one that compares daily rainfall values to evapotranspiration rates to determine rate of soil moisture depletion to give up to date status of available soil moisture after correcting for surface runoff, and expresses these relationships in terms of drought effects on crop growth at various stages of crop development. Again, the threshold levels of soil moisture for defining incidence and severity of drought may vary from crop to crop and soil to soil. A very general form of an operational drought index for a given region could be one that compares total available water in different forms e.g. surface water, soil moisture & groundwater on a weekly/monthly basis to the expected demand of the region to give up to date position of water deficit in terms of drought effects on the various established water uses and society as a whole. The shortage of water in its different forms along with the degree of dependence of the society on various forms of water and time distribution of the demand are very important for development of an overall operational drought index. The hydrological drought indices using numerical numbers indicating on set and severity of drought are hardly found in the literature. Whereas in meteorological and agricultural fields such drought indices, although by and large adhoc in nature, have been developed for various purposes. No theoretical work has been done in past on the construction of simple hydrological drought index. Development of a Surfac Water Supply Index (SWSI) as a drought severity indicator for colorado, USA by Dezman et al. (1982) is one exampale of hydrologi lrought index parallel to Palmer drought index basically developed as a meteorologic drought index.

6.6 Since drought has different connotations for different uses and disciplines, there can not be a single universal definition of drought.

A method based on meteorological or agricultural or hydrological variables alone may not provide the assessment of drought in its totality. However, a broad perspective of water deficiencies in meeting various water needs could form the basis of a drought definition. Therefore, an overall integrated picture based on all the factors affected by drought could give a better picture of drought incidence and its severity in any region. This calls for the development of an integrated, interdisciplinary sets of drought indices. An integrated scheme for classification of droughts proposed by Ramana Rao et al. (1982) giving equal weightage to agricultural droughts and drought conditions based on departures from raianfall and aridity index may be considered as one such step in this direction. Surface Water Supply Index is another such example to provide an objective indicator of water supply conditions in a river basin. An overall integrated drought index should take into account rainfall, surface water, soil moisture and groundweater components giving due weightages to each of these as per the demand pattern of the region.

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APPENDICES

Appendix - I

DROUGHT DEFINITIONS BASED ONLY ON ABSOLUTE VALUE OF RAINFALL AMOUNT AND DURATION OF DRY PERIOD

Sl. No.	Author	Year	Definition/Associated concepts	Region	Remarks
1.	-	1964	Period of 6 days without rain	Bali	
2.		1964	Period of 2 years without rain	Libya	
3.	Brounov	Early 20th Century	Ten days with rain fall not exceeding 5mm	Russia	WMO(1975)
4.	Cole	1933	Fifteen days without rain	U.S.A.	-do-
5.	British Rainfall Organisation	1936	Absolute drought: at-least 15 consecutive days none of which received as much as 0.25 mm Partial drought: at-least 29 days during which mean rainfall does not exceed 0.25 mm per day. Dry spell: 15 consecutive days none of which has received as much as 1 mm.	U.K.	-do-
6.	Blumenstock	1942	Less than 2.5 mm in 48 hours	U.S.A.	-do-
7.	Conrad	1944	A period of 20 (or 30) consecutive days or more without 6.4 mm of precipitation in 24 hours during season. (March to Sept. inclusive).	U.S.A.	-do-
8.	Fitzpatrick	1953	Period teminated by at least 6.4 mm during any 48 hours.	Australia	-do-

10.	Goodridge	1967	The accumulated average daily rainfall for the period in which no effective rainfall occurs; Effective rainfall being the lower threshold value of daily rain which is significant in various applications of this index.	U.S.A.	(cited from Yevjevich, 1977) -do-
11.	IMD	1971	Drought is said to occur when the annual rainfall is less than 75% of the normal. Severe drought is said to occur when the deficieney of rainfall is above 50% of the normal.	India	

Appendix-II DROUGHT INDICES BASED ON RAINFALL CHARACTERISTICS AT A PLACE COMPARED WITH A LONG TERM AVERAGE AT THE PLACE

Sl. No.	Author	Year	Definition/Concept	Region	Remarks
1.	Henry	1906	21 days or more when Rainfall is 30% or less of average for the time and place. Extreme drought when rainfall fails to reach 10% of normal for 21 days or more.	U.S.A.	WMO(1975)
2.	Hazen	1916	The coefficient of variation of the annual rainfall exceeds 0.35	Western USA	(cited from chow, 1964)
			The coefficient of variation of annual rainfall is between 0.15 to 0.25	Eastern USA	
3.	Bates	1935	When annual precipitation is 75% of the normal or when monthly precipitation is 60% of normal.	U.S.A.	WMO(1975)
4.	Hoyt	1936	Any amount of rainfall less than 85% or normal	U.S.A.	-do-
5.	Baldwin-Wiseman	1941	Engineer's drought: Three or more consecutive months with deficit of 50% from mean rainfall.	Australia	-do-
6.	Tennesse Valley Authority	1944	No interval of 21 days received precipitation greater than one third of normal.	U.S.A.	-do-
7.	Ramdas	1950	When actual rainfall for a week is half of normal or less	India	
8.	Foley	1957	Computed Residual mass curves of rainfall departures and developed a dimensionless drought severity Index by dividing the values obtained by average annual rainfall.	Australia	-do-
9.	Ramdas	1960	A year is considered is a drought year when the rainfall is less than normal by twice the standard deviation of the series.		

Indices based on Rainfall and mean temperature

Author	*Definition of drought or associated concepts*	*Region and comments*
Lang (1915)	Precipitation factor = P/T P in mm, T in °C	Germany. Developed to aid climatic classification of soils.
de Martonne (1926)	Index of aridity $I = \frac{P}{t + 10}$ where P is monthly precipitation (mm) and t is mean monthly temperature (°C). Monthly index of I is approximate indicator of aridity.	Used to define climatic limits of deserts, prairies and forests. Does not apply well in cool zones where $t + 10$ approaches zero.
	Index modified to $I = \frac{n \cdot \bar{p}}{t + 10}$ where n is number of days during a certain period from a few days to a year and $\bar{p}$ is daily mean precipitation in the period.	Used extensively by geographers and biologists to compute aridity.
Koloskov (1925)	Ratio of annual precipitation to accumulated mean daily temperature during vegetation period (divided by 100).	U.S.S.R. Ratio may be used as a comparative agroclimatic index.
Selyaninov (1930)	Index given by $k = \frac{\Sigma p}{\Sigma t/10}$ where p is sum of rainfall (mm) during those months when mean temperature is above 10 °C and t is the sum of the daily mean temperatures above 0°C for the same period.	U.S.S.R. Author suggested that a period be considered as a dry spell when $k < 1$ and as a drought when $k < 0.5$.
Koppen (1931)	*Defines "dry" climate by:* $p < 2t$ for regions of winter rain and $p < 2t + 14$ for regions of summer rain or no rainy season where p is annual precipitation in cm and t is mean temperature in °C. *"Desert" climate defined by:* $p < t$ for winter rain; $p < t + 14$ for summer rain; $p < t + 7$ for no rainy season.	Used extensively in classification of the dry climates of the world.
Emberger (1955)	$I = \frac{100p}{(M - m)(M + m)}$ where M is the mean maximum temperature in the hottest month and m is the mean minimum temperature in the coldest month; p in mm and M and m in °C.	France. Based on de Martonne's index, (M - m) is an index of continentality.

Source: WMO (1975)

Author	*Definition of drought or associated concepts*	*Region and comments*
Knochenbauer (1937)	Daily maximum temperatures and humidity at time of afternoon observation used to define a dry spell.	Germany.
Condra (1944)	Period of strong wind, low precipitation, high temperature and usually low relative humidity.	U.S.A. This anticipates the combination of low precipitation and high evapotranspiration.
Henin and Ternisien (1944)	Computed evapotranspiration and drainage from temperature and precipitation.	France. Procedure improved by Turc (1954) incorporating additional factors.
Popov (1948)	Index of aridity $P = \frac{\Sigma g}{2.4\,(t-t')r}$ where P is index of aridity; Σg is annual amount of effective precipitation; $t-t'$ is annual mean wet-bulb depression °C; r is factor depending on day length; and g is that part of precipitation which is available for plants.	
Thornthwaite (1931)	Precipitation effectiveness as a function of mean temperature. $P/E = 1.65\left(\frac{P}{T+12.2}\right)^{(10/9)}$ in mm and °C where P/E is the precipitation evaporation ratio, P is monthly precipitation in mm, and T is monthly mean temperature in °C.	U.S.A. See also under "Climatic indices and estimates of evapotranspiration". Table 1 *(d)*.
Gaussen (1954)	When total monthly precipitation in mm is less than twice the mean temperature in °C.	An approximation to rainfall less than evapotranspiration based on Köppen.
Budyko (1970)	Hydrothermal coefficient $K = \frac{r}{0.18\Sigma 0}$ *where* $0.18\Sigma 0$ gives the potential evapotranspiration in mm, $\Sigma 0$ being the annual sum of daily mean temperatures higher than 10°C; r is annual precipitation in mm.	U.S.S.R.