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DROUGHT ESTIMATION AND CONTROL

STATUS REPORT

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ABSTRACT

Droughts form one extreme end of the hydrologic cycle, while floods are at the other end. Drought is a frequent hazard in India, striking in some part or the other. The most striking effect of droughts is that they cause local as well as regional imbalances and retard the economy of the nation. In spite of technological advancements made in this direction, still it continues to be a major factor of uncertainty.

The definition of term drought varies widely with area of interest and the kind of user. An extensive review of the available literature on drought has been made. The intensity of drought classification based on the parameters like climatological, parameters, soil moisture, evapotranspiration, plant factors, low stream flow levels or ground water levels etc. has been discussed. The commonly used drought indices have been also reviewed. Drought studies by water budget method, Palmer drought indices and associated two layer approach have been discussed in detail. The various mathematical, statistical and stochastic approaches to investigate the incidence, trend and prediction of drought have been dealt with.

An attempt has been made to review the impacts of droughts on various aspects e.g. agricultural production, morphology, land regime, reduction of water level in different

water bodies, water quality, socio-economic conditions etc.

The strategies for minimising the impacts of droughts both long and short term have been reviewed with special emphasis on development conservation, and utilisation of water resources adapting integrated land and water management approaches on watershed basis. Means of artificial recharging of groundwater have been also discussed.

It appears to be that there is no general agreement on definitions and methods of describing the drought phenomenon. On the basis of review made, the present state-of-knowledge on drought; existing technological gaps and future research needs have been briefly mentioned in the report.

1.0 INTRODUCTION

1.1 General

Droughts and floods are the two sides of the same coin both being the extremes of the hydrologic phenomena. Drought, the precursor of famine, represents creeping type disaster, usually involving long durations of water deficit. Flood damages to society are much more visible than the droughts. Over the years, drought impacts have been felt in agriculture, energy production, pollution, recreational facilities and other such activities which ultimately reflect on the economy of a nation. The problem of drought is a global phenomenon. World Meteorological studies indicate that in recent past (1968 to 1979-80), severe droughts have affected African sahel, parts of India, part of Brazil, Queensland in Australia, Central America and Mexico.

1.2 Nature and Extent of Problem

Drought is a frequent hazard in India, striking in some part or the other. It is not only confined to arid and semi-arid regions but often visits potentially good rainfall areas too, which are otherwise productive (i.e. humid and sub-humid rainfed agricultural areas). In this century, the country had severe droughts in the years 1907,1911,1918,1920, 1939,1951,1965-67,1972-73 and 1979.

During the 1979 drought, as reported by Srivastava (1979), crops over nearly 35 million hectares in 12 States viz,, Andhra Pradesh, Bihar, Madhya Pradesh, Himachal Preadesh Rajasthan, Orissa, Jammu and Kashmir, Punjab, Haryana, Maharashtra, Uttar Pradesh and West Bengal involving about 200 million people have been affected in varying degrees. During the 1965-67 droughts, which affected 156 districts of the country, expenditure on drought relief was 722 crores of rupees. During the two consecutive droughts of 1971-72 and 1972-73, the expenditure was nearly Rs. 790 crores for the 227 affected districts and during the 1979 drought, nearly Rs.160 crores was approved by Government of India(Jaiswal, 1981). The recurrent incidence of droughts has been causing local as well as regional imbalances and continues to be one of the heaviest drag on the growth of national economy.

The problems posed by droughts vary from area to area depending upon the amount of precipitation and its variability and on the demand of water for the specified user. The term drought has different connotations for different users. In general terms, it is lack of water with respect to a specific need in a conceptual supply and demand relationship. Nearly 75% of the cultivated area of the country is rainfed, receiving mean annual rainfall of 400-1125 mm in 2 to 5 months and about 42% of the nation's food production is from these dry land areas. Therefore, any violent fluctuation of rainfall would seriously affect the food situation of the country. Estimates of food grain production indicate that minimum percentage reduction in food grain production was 12.9 during the drought year 1907-08 and maximum 32.3 during the drought year 1918-19.

Occurrence of drought results in reduced stream flows, reservoir levels, ground water levels and soil moisture levels. It not only affects the quantity but the quality of water too, if it is prolonged. Morphology of streams is also influenced due to occurrence of droughts. Reduced discharges during drought periods reduce the sediment carrying capacity of the river causing bed aggradation, with consequent induced braiding in the streams.

Its occurrence appears to have multiplier effect in the process of desertification. It disturbs the ecological balance of the region. The arid regions of Rajasthan characterised by low rainfall, high temperature and high wind velocities are the living example of this. It has been estimated (Anon.1973 ; cited from Das & Mukerjee,1980) that three million people with their live stock migrate annually from these regions in search of food and forage.

1.3 Scope of the Study

As indicated earlier, the droughts have multi-dimensional problems of varying intensities. Broadly, droughts have been classified as meteorological, hydrological and agricultural droughts (National Commission on Agriculture,1976). However, drought is generally understood to be a moisture deficiency of such magnitude as to adversely affect the accustomed human activities of the region.

The literature on drought is voluminous, presenting different aspects of drought. Due to diversity of definitions for drought, the investigation of its characteristics, impacts, trends and prediction and thereby management of drought control strategies is a problem. Drought estimation and control is one of the areas of the research in the workplan of National Institute of Hydrology. Attempts have been, therefore, made in this status report to review the available research findings on drought estimation and control with an objective to clearly spell the present state-of-knowledge on the subject and to identify technological gaps so as to plan the future research needs in this direction.

2.0 QUANTIFICATION OF DROUGHT

2.1 General

Drought differs from aridity in a sense that aridity is a permanent climatic feature of a region and restricted to regions of low rainfall and high temperature. Drought, on the other hand is a temporary phenomenon, experienced only when precipitation falls appreciably below normal and is virtually possible in any rainfall or temperature regime.

The very first step in investigating any problem and finding its solution, is the definition of the problem itself. One of the main obstacles in drought investigations is the wide diversity of definition itself. There is no universally accepted objective definition of the drought. The definition and particularly the quantification of drought is still controversial, perhaps because the concept is not absolute but relative to uses or needs and expectations. However, in very general terms ' drought is a condition of moisture deficit sufficient to have an adverse effect on vegetation, animals and man over a sizeable area' (Warrick 1975 ; cited from Yevjevich et.al.,1977). According to Krishnan(1979) drought is a general term implying a deficiency of precipitation of sufficient magnitude so as to interfere with some phase of the economy.

As already stated every water use may need its own concept of drought. In agriculture, it means a prolonged shortage of moisture in the root zone of crops and often related to critical growth stages of plant. To a hydrologist, it may mean below average content in streams,reservoirs, groundwater aquifers lakes and soil. In economic sense, it may mean water shortage which significantly alters or disturbs established production base and water uses. The concept of drought may change even for the same water use with time,place and specified need. For example, a drought for the grower of tomatoes may not be a drought for the grower of potatoes. Therefore, supply and demand both are essential for proper understanding of droughts.

National Commission on Agriculture (1976), broadly classified droughts into the following three types :

i Meteotological drought

It is a situation when there is significant (more than 25 percent) decrease from normal precipitation over an area.

ii Hydrological drought

Meteorological drought, if prolonged results in hydrological drought with marked depletion of surface water and consequent drying up of reservoirs, lakes, streams/rivers, cessation of spring flows and fall in groundwater levels. Hydrological drought may be reflected in depleted snowmelt due to poor snow fall in an earlier season and this may result in the curtailment of user needs and badly affect both the industry and the agriculture.

iii Agricltural drought

It occurs when soil moisture and rainfall are inadequate during the growing season to support healthy crop growth to maturity, and cause extreme crop stress and wilt. An agricultural drought may exist even though meteorological drought may not, and vice-versa.

2.2 Parameters used in Quantification of Drought

Studies of past droughts around the world have led to over 60 definitions and quantification of drought using different variables either singly or in combination. Generally, the parameters used to define drought are rainfall,temperature, humidity, evaporation from free water, evapotranspiration,soil moisture, critical growth stages of crops,crop yield, land use, surface runoff and resulting stream flows, reservoir levels, ground water levels etc. Several studies have been made to quantify droughts using these parameters and evolving certain indices like aridity, humidity, Palmer, climatic crop growth indices etc. These variables have been grouped into meteorological,crop, and hydrological parameters for easy and better understanding of the phenomena.

The quantification of drought based on meteorological, crop and hydrological variables and set of indices has been reviewed here.

2.3 Meteorological Parameters

Drought is a meteorological phenomenon as it is caused due to deficient rainfall. Early workers defined drought as prolonged period without rainfall. Subsequently, other meteorological parameters like temperature, humidity, sunshine, radiation and wind were also used in combination with rainfall to quantify drought.

2.3.1 Relation to actual Rainfall

In USA during the early days, commonly used definition of drought was a period of 21 days when rainfall is 30% less than the normal for the place and time (Tannehill,1947 cited from Yevjevich et.al,1977). Many others including (Henry, 1906; Cole,1933; Bates,1935; Hoyt,1936 ; Bluemen Stock,1942; Condra,1944 and Linsley et.al.,1959; cited from WMO,1975a) defined drought using different threshold values. The areas most subjected to drought are those in which the variations in annual rainfall are relatively greatest. Hazen (1916; cited from Chow,1964) showed that , in the area of Western United States that have frequent droughts, the coefficient of variation of the annual rainfall exceeds 0.35 and that, where droughts are less frequent and less severe in East, the coefficient of variation of annual rainfall varied from 0.15 to 0.25. Low total precipitation and high variability tend to go hand in hand because, where the total annual precipitation is small it is generally due to a relatively small number of storms or rainy periods. Since the number of events involved are small, it is natural that the variability will be great.

Herbst et.al.(1966,cited from Yevjevich et.al.,1977) developed a technique for evaluating droughts by using monthly precipitation. The technique determines duration and intensity of droughts as well as the months of their onset and termination. It permits the comparison of drought intensities irrespective of their seasonal occurrence. Goodridge(1967 ; cited from Yevjevich et.al.,1977) defined the drought index as the accumulated average daily rainfall for the period in which no 'effective rainfall' occurs. Effective rainfall is considered as the lower threshold value of daily rain which is significant for various applications of this index. This index is used to find frequencies of extreme droughts for various values of effective rainfall. In Australia, Foley (1957 ; cited from Subrahmanyam,1967 and W.M.O.,1975) computed residual mass curves of rainfall departures and developed a dimensionless ' Index of drought severity! This is a variation of the residual mass curve in which departures of rainfall from average for each specified period, e.g. monthly, are cumulated. The method divides each monthly anomaly by the average annual rainfall, then divides by 1000, and cumulates the dimensionless "units" so obtained. Figure 1 is an example of the temporal presentation of drought data.

Deciles of rainfall, the commonly used approach was advanced by Gibbs & Maher (1967; cited from WMO,1975b). In this method the limits of each ten percent (or decile) of the distribution are calculated from a cumulated frequency curve or an array of the data. Thus the first decile is that

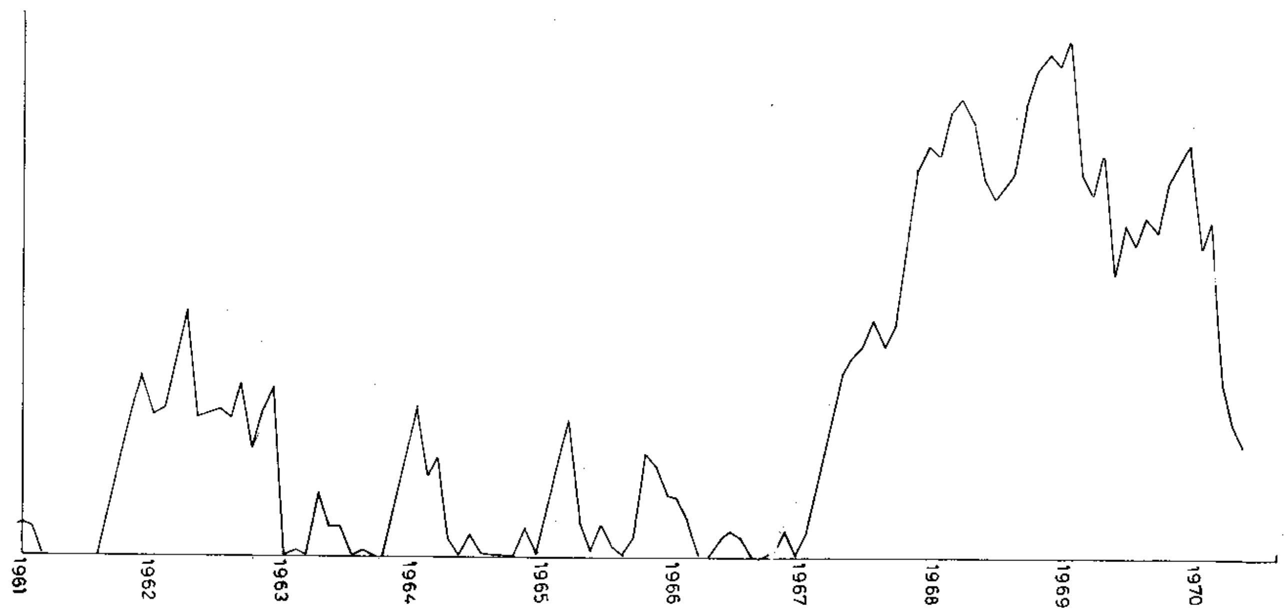

FIGURE 1 - FOLEY DROUGHT INDEX FOR MELBOURNE

rainfall amount which is not exceeded by ten percent of totals the second decile is the amount not exceeded by 20 percent of totals and so on. The fifth decile or the median is the amount not exceeded on 50 percent of occasions. The decile ranges are the ranges of values between deciles. Thus the first decile range is that below the first decile, the eight decile range between deciles seven and eight. Figure 2 illustrates this concept. Normally the square root of rainfall is plotted on the abscissa.

The area under the curve for any given range of rainfall indicates the frequency or probability of occurrence within that range; thus there is an equal probability of rainfall failling in any decile range and the number of the decile range indicates" dryness" or " wetness " with respect to "normal". The first decile range suggests abnormally dry and the tenth decile range abnormally wet conditions. They proposed the use of deciles of annual rainfall as drought indicators and concluded that the occurrence of the first decile range corresponds well with droughts in Australia.

The British Rainfall Organisation(1936; cited from WMO, 1975a) drought is a period of more than 28 days with a very small rainfall per day and ' absolute drought' is a period of at least 15 consecutive days to more of which is credited as much as 0.25 mm of rain (WMO 1975). In USSR drought is defined as period of 10 days with a total rainfall not exceeding 5 mm, whereas in New Zeland,Agricultural drought is said to exist when the soil moisture in the root zone is at or below the permanent wilting point(WMO,1975a). Ramdas et.al.(1948)

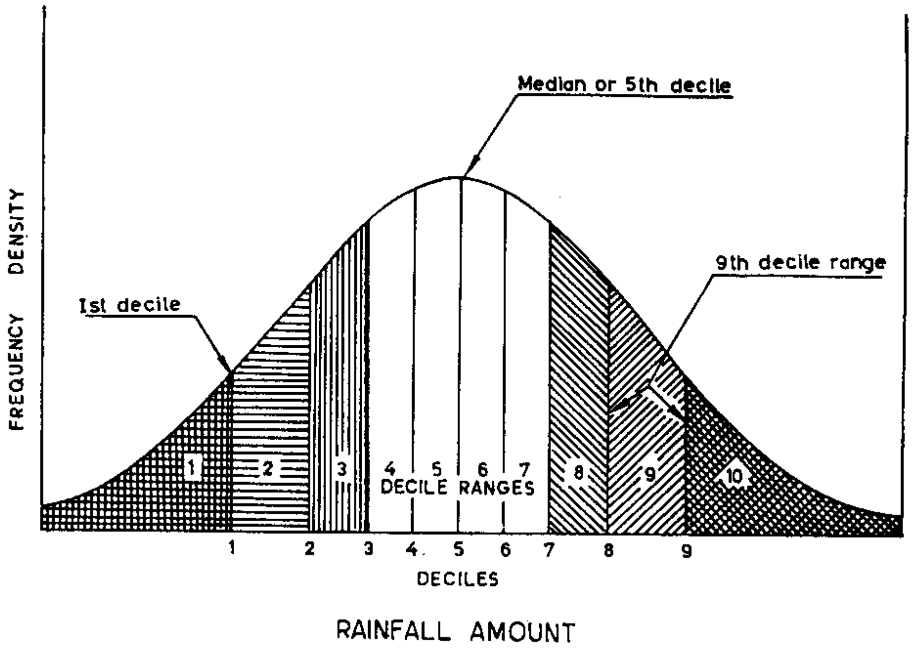

FIGURE 2- ILLUSTRATING USE OF DECILES AND DECILE RANGES

defined the drought as a week with actual rainfall equal to half the normal rainfall or less (cited from Subramaniam et. al.,1979). Malik(1963),Govindaswamy (1958) and Malik & Govindaswamy (1962-1963) studied weekly rainfall abnormalities adapting the Ramdas criteria and defined the incidence of agricultural droughts assuming that drought has repercussions on crop growth only when it extends over 4 or more consecutive weeks. Ramdas (1960) considered a year as drought affected when rainfall is less than normal by twice standard deviation of the series.

Monthly rainfall deciles (i.e. limits of each ten percent of the distribution) approach as developed by Gibbs and Maher(1967) for Australia, was used by George & Kalyansundaram (1969; cited from George et.al.,1973) to study droughts in Bihar. Kalyansundaram & Ramasastri (1969) studied drought in Bihar using Van Roy's drought anomaly index with slight modification

$$\text{Van Roy's Index,} \quad I = -3 \; \frac{P - \bar{P}}{\bar{m} - \bar{p}} \qquad \ldots(1)$$

where,

I is anomaly index ;

P is actual precipitation ;

$\bar{P}$ is the normal precipitation and

$\bar{m}$ is the mean of the ten lowest values of recorded P.

But they used $m = 3/4\ \bar{P}$, in above index.

India Meteorological Department has defined drought as a situation occuring in a sub-division in a year when the annual rainfall is less than 75 percent of the normal. When the deficiency of rainfall is above 50% of the normal, it is termed as ' severe drought'. Taking a long period of 60 years or so, areas where drought has occurred in 20 percent of the years during the period are considered' drought areas', and where it has occurred in more than 40 percent of years, as chronic drought areas'. This definition of drought does not take into account the distribution of rainfall so importa-nt from the point of view of agriculture. However, in view of the differences in cropping patterns and distribution of rainfall from region to region, it is difficult to offer the definition of drought with sufficient exactness by intro-ducing this element. Using the annual and southwest monsoon rainfall data from 1901 to 1960 for about 500 stations, the Irrigation Commission (1972) identified the following drought and chronic drought areas in the country :-

a)	Drought area (20% probability of rainfall deficiency of more than 25 percent of normal	i)	Gujrat,Rajasthan and adjoin-ing parts of Punjab, Haryana West Uttar Pradesh,and West Madhya Pradesh.
		ii)	Madhya Maharashtra,Interior Mysore, Rayalaseema,South Telangana and parts of Tamilnadu.
		iii)	A small portion of northwest Bihar and adjoining east Uttar Pradesh.
		iv)	A small portion of northeast Bihar and adjoining portion of West Bengal.
b)	Chronically drought affected areas (40%) probability of rainfall deficiency of more than 25% of normal)		South Western Rajasthan and Kutch

Thus, most of the areas identified as susceptible to drought fall within the arid and semi-arid zones. Chronically drought affected areas are identical with the intensely arid zone. All the districts which comprise the drought zone are not equally vulnerable to crop failures as protective irrigation has been developed in some district or taluka. As such, those of the districts/tehsils which enjoy a minimum percentage of irrigation should appropriately be excluded from the list of drought affected areas.

Probability of occurrence of 'dry spell' of short and long duration (ranging from few days to few weeks) have been also tried by Ratnam et al.(cited from Correia and Bohra, 1980), Ramana Rao et.al.(1976), Victor & Sastry (1979) and many others for different places.

Correia & Bohra (1980) studied the incidence of drought and its long term forecast in Udaipur using the criteria of British rainfall organisation. Accordingly they classified droughts into 3 classes, viz., absolute drought,partial drought and dry spell , after analysing the daily rainfall data.

2.3.2 Rainfall and temperature

Index of aridity, $I = \frac{P}{t + 10}$ was developed by de Martonne in 1926 to compute aridity where,P is monthly precipitation (mm), and t is mean monthly temperature (°C)

Further, index was modified to

$$I = \frac{n.\bar{P}}{t+10} \quad ...(2)$$

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. This index was mainly used in Germany to compute aridity by geographers and biologists.

Thornthwaite (1931; cited from WMO,1975a) developed a precipitation effectivenss index as a function of rainfall and mean temperature.

Selyaninov (1930; cited from WMO,1975a) gave an index

$$K = \frac{P}{t/10} \qquad \ldots(3)$$

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 o°C for the same period.

The period when K is less than 0.5, it is considered to be a drought.

The quantification of the drought using rainfall alone or in combination with other meteorological parameters does not appear to be suitable approach as it does not account for soil and crop parameters. Criteria developed on the basis of rainfall alone appears to be misleading.

2.4 Commonly Used Drought Indices

Set of variables e.g. climatic, soil and crop have been used to arrive at certain drought indices. The commonly used drought indices have been discussed here.

2.4.1 Aridity and humidity indices

In the preceeding section, drought has been defined on the basis of actual rainfall alone which does not appear to be appropriate. In past, studies have been directed towards evolving an agro-climatic index of drought incidence over the country. Subrahmanyam and Co-workers (1964,1965) made use of the aridity index of Thornthwaite instead of the mere water deficiency to define drought characteristics and classified the drought into varying intensities using standard deviation (σ) of aridity index. The yearly march of aridity index was plotted and the amplitude of departure of the index from its normal value was taken to represent the severity of the drought on annual basis.

According to Thornthwaite & Mather(1965;cited from Subrahmanyam & Sastri,1971), in working out the water balance of any region, precipitation is considered as 'income' and potential evapotranspiration(maximum amount of water loss by way of evaporation and transpiration with unrestricted water supply) as " expenditure", allowing a maximum amount of 300 mm of water from rainfall to be retained in the soil as soil moisture. Potential evapotranspiration (PE) is also called the water need. When precipitation is greater than the PE, the excess goes into the soil until the later is saturated and the surplus, if any, is called water surplus, which flows out as runoff. On the other hand, when the precipitation is less than the water need(PE), the entire precipitation and a certain portion of the soil moisture(depending upon the amount of the stored soil moisture and the atmospheric demand) are utilized for purpose of evapotranspiration. This is called the actual evapotranspiration (AE), which in this is equal to the precipitation plus the change in soil moisture storage while in the former it is equal to PE. However, when the amount of AE falls short of water need (i.e. PE), then water deficiency arises, which is measured as the difference between PE and AE.

Aridity Index is defined as the ratio of annual water deficiency to annual water need expressed as a percentage. Thus

$$\text{Aridity Index } (I_a) = \frac{PE-AE}{PE} \times 100 \qquad \ldots(4)$$

Employing a purely statistical procedure, the drought years were classified into various intensity classes as below:

Departure of aridity index from normal	Drought category
Less than $1/2\sigma$	Moderate
$1/2\,\sigma$ to σ	Large
σ to 2σ	Severe
Greater than $2\,\sigma$	Disastrous

The water deficiency in any particular month of a given year may vary considerably from its climatic value and the deviation is called the departure of monthly water deficiency. Such departures, when successively determined and added together algebrically over a specified period, give the cumulative water deficiency or ' cumulative deviation'.

The studies of drought analysis for different regions of south India have been conducted by Subrahmanyam & Sastri

(1968,1971) and Subrahmanyam et.al.(1972;cited from Subrahmanyam et.al.,1982) with slight modifications. Maps depicting the changing patterns of aridity for the sequential drought situation and cumulative deviation diagrams have been presneted (Subrahmanyam and Sastri,1971).

Though the criteria of drought intensity classification are suitable for arid zone, the same may not be the case in respect of semi-arid and sub-humid zones, since aridity indices in these regions are comparatively small with high coefficients of variation,Krishnan & Thavi (1971;cited from Krishnan,1979) therefore used the following criteria for Kharif cropping season in Rajasthan, since monsoon season accounts for nearly 90-95 percent of annual rainfall.

Aridity index in Kharif season	Drought Intensity
50 to 60	Slight
60 to 70	Moderate
70 to 80	Severe
More than 80	Disastrous

This study indicated that droughts were more common (60-90%) than good years in arid zone. Drought years constituted 6 to 20 percent in semi-arid and 5 percent in sub-humid zone of Rajasthan. A study of droughts of 1965 and 1966 Kharif season in India was made by Chowdhury et.al.(1977;cited from Krishnan, 1979)by working out aridity anomalies and using following intensity classification:

Mild drought	25
Moderate drought	26 to 50
Severe drought	more than 50

Considering that anomaly criteria may over-estimate drought in semi-arid and sub-humid zones,Krishnan et.al.(1978)

and Krishnan & Rao (1979; cited from Krishnan,1979) defined moderate and severe drought periods using the following criteria and using weekly water budgeting procedure :

1. Moderate drought - period for which

   $\frac{PE}{2} > AE \geq \frac{PE}{4}$, and

2. Severe drought-period for which $AE < \frac{PE}{4}$

Seth et.al.(1979) used aridity index and moisture index values, applying Thornthwaite & Mather (1955) book keeping procedure for water balance to study frequency of droughts in North Western India.

$$\text{Humidity Index}, l_h = \frac{\text{Annual moisture surplus}}{\text{Annual PE}} \times 100$$

Moisture Index, $l_m = l_h - l_a$

where l_a, is aridity index.

Potential evapotranspiration values were assumed to be constant from year to year in their study may be due to unavailability of the data. But however, drought studies are very sensitive to assumed PE values.

Subramaniam & Rao (1982) studied climatic droughts using the similar approach of Subrahmanyam & Subramaniam (1965) and using median as the base, a reference for measuring the departures (Subrahmanyam et.al.,1972). Similar studies were carried out by Sarma & Ravindra (1982) but they used exponential smoothening technique advanced by Stevenson to effectively filter the undesired components, such as random and irregular in time series of aridity index.

The equation used is,

$$V_s = V_{s-1} + \alpha \ (D - V_{s-1}) \qquad \ldots(5)$$

where,

V_s = Newly smoothed value

V_{s-1} = previously smoothed value,

D = Next data point, and

α = smoothing factor which depends on the number of observations

Thornthwaite & Mather(1955) book keeping approach of water balance has been extensively adapted by the workers for computing water deficit and surplus. Subba Rao & Subrahmanyam (1961;cited from Krishnan,1979),Rao et.al.(1970,cited from Srivastava et.al.,1977),Srivastava et.al.(1977),Chatterjee et. al.(1978;cited from Krishnan,1979),Subrahmanyam & Upadhyay(1983) have used this approach for studying the water balance of different river basins using Thornthwaite(1948) method of computing potential evapotranspiration. They have rather preferred to use the term water deficit in place of drought.

Rao et.al.(1976) studied the climatic water balance of India using similar approach,computing potential evapotranspiration by modified Penman's method. Sastri & Malakar(1981) and Apparao (1982) analysed the agricultural droughts using this approach for obtaining anomalies.

It is understood that the identification and classification of drought by aridity indices during crop growing season using improved water balance computations for shorter intervals (say weekly or still shorter periods) would be much more useful than doing the same on only rainfall data. Improvement of water balance model by using soil moisture characteristics, root zone, stage of crop growth, use of actually measured soil drying curves and evapotranspiration would prove to be better in drought studies.

2.4.2 Moisture adequacy index

The moisture adequacy index (IMA) defined as ratio of actual evapotranspiration (AE) to potential evapotranspiration (PE) expressed as a percentage was first used by Subrahmanyam et.al.(1963; cited from Subramaniam & Sastri 1979) to study agricultural drOughts in India. They concluded that most of the agricultural crops in India do not seem to have favourable conditions for development below 40% value of the index of moisture adequacy. Based on this Subrahmanyam & Sastri,1979) studied agricultural drought in different regions of Andhra Pradesh. The moisture adequacy index (IMA) was evaluated using water balance computations for the growing seasons of three rainfed crops i.e. pearl millet, sorghum and finger millets. They incorporated the minimal value of the index of moisture adequacy, above which yield would be always higher than the average yield and below which the yield would be lower than the average yield. Minimal values of IMA for 3 crops of two different stations were worked out by plotting years (on abscissa) and the values of IMA (on ordinate). For each individual year the yield was marked against the corresponding IMA value. A line was drawn parallel to x-axis above which the yields are always higher than the average and vice-versa as shown in Figure 3.

The departure of the index of moisture adequacy expressed as percentage from the minimal required value was used to classify agricultural droughts which are different for different crops and regionss

Departure of IMA(%) below the minimal value	Agricultural drought intensity
Less than 10	Moderate
10 to 20	Large
20 to 30	Severe
More than 30	Disastrous

The approach to classification of drought intensity and fixing of minimal value appears to be arbitrary. An objective assessment of this value and departure therefrom for intensity classification could probably be more enlightening. Phenological stage may be introduced in assessing the drought intensity in a better way and advocating suitable water management techniques.

2.4.3 Palmer index

Palmer (1965; cited from George et.al.1973) developed drought index known as Palmer Index. Based on the water budget of the soil, Palmer used the difference between actual precipitation and required precipitation under conditions of average climate in an area to evaluate drought severity in space and time. It takes into account precipitation, potential evapotranspiration (Thornthwaite method), antecedent soil moisture conditions, an estimate of available soil moisture and runoff.

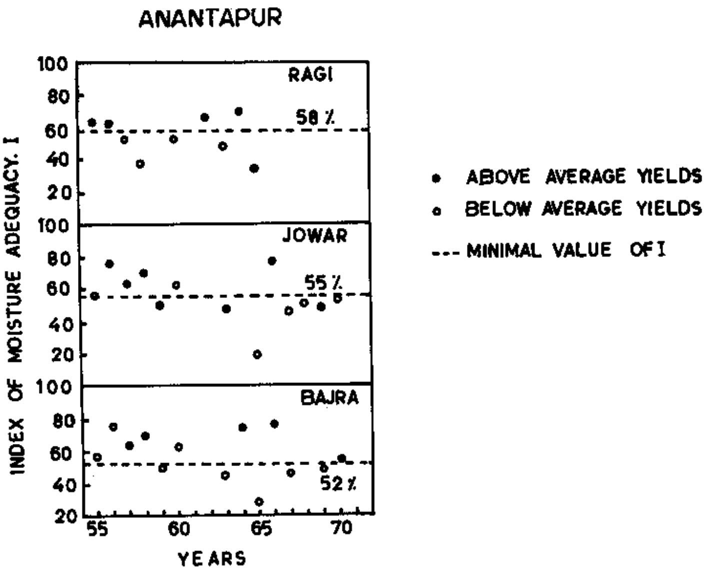

FIGURE 3 - CROP YIELDS AND MOISTURE ADEQUACY IN ANDHRA PRADESH (1955-70)

This index has been widely used in USA and in some other areas of the world. Results are reported to be realistic in USA. It is basically an index of meteorological drought. The method requires a month-by-month water balance accounting for a long record, such as 30 years or more. 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 capacity 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 empirical weighting factor and drought severity equation has been used to analyse drought. The procedure for computation of Palmer Index is given in Appendix-I.

Palmer (1968; cited from WMO,1975a) developed an agricultural drought index based on successive weekly values of the computed abnormal evapotranspiration deficits. Such indices are taken into account in the weekly weather and crop bulletin issued by the National Oceanographic and Atmospheric Agency of USA.

On the lines of work done in USA by Palmer, computations involving detailed hydrologic accounting were carried out by George et.al.(1973) for 150 stations of different meteorological sub-divisions for the period 1970-71 to study incidence of droughts in India. Thornthwaite (1948) method for computing potential evapotranspiration was used.

They tried to compare the drought period as obtained by Palmer Index with crop conditions and the yield. It was observed that the occurrences of well known drought spells in Bihar and Tamilnadu were in agreement with computed Palmer indices. It is,however,noticed that the frequency and duration of drought months were considerably 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 sub-divisions of India. Percentage occurrences of droughts of class moderate and above in Kharif season have been given in Table 1. This overestimation may be due to non-applicability of empirical weightage factor derived from American conditions to our situation. 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 so. This may be due to the considered abnormalities in evapotranspiration,soil moisture and runoff as well,which are appropriate for the area. It is to be noted that the first two parameters are concerned more with agricultural drought and so the Palmer index indicates the intensity of agricultural droughts in semi-arid and dry sub-humid areas. Similarly in humid and moist sub-humid areas, runoff will significantly govern the value of Palmer index first than the other factors and rainfall deficiency will affect runoff first and later the other factors which are of direct concern to crops. Thus index here represents hydrological drought as stated in their study.

The weighting factor and drought severity equation developed by Palmer may not hold good strictly in all the

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-divisions of India as it is specially designed for semi-arid and dry sub-humid regions of USA. Thinking on these lines, Balme & Mooley (1979) have attempted to introduce modified weighting factor and severity equation for Indian conditions using data of 21 districts. They have also used Thornthwaite method for computing evapotranspiration.

It has been indicated that defective weighting factor convert large moisture deficiency into a small moisture surplus. The modified weighting factor now always have been reported to give rise to positive weights and the modified severity equation gives much higher weightage to the current moisture anomaly. Power spectrum analysis of the series of the seasonal mean modified drought index for 10 years, reveals a period near 10 years, corresponding to sunspot cycle over north west India. Severe drought conditions have been reported to occur in the next year after sun spot maximum. It is yet to be tested for different regions of the country.

To study agricultural droughts in a better way, it is necessary to use shorter periods say weeks instead of months. Since the method is very much dependent on evapotranspiration estimates, improved method of estimating evapotranspiration may be better. The weekly Palmer Index values using Penman or modified Penman method for computing evapotranspiration may be more useful for drought studies.

2.4.4 Climatic-crop-growth indices(CCGI)

Climatic-crop-growth indices advanced by Prescott in Australia, utilise plant-soil-rainfall interaction concept and uses different ratios of pan evaporation to classify intensity of droughts (cited from Das et al.,1980).

$$CCGI = P/ E_w^{0.75} \qquad \ldots(6)$$

where, P = rainfall, and

E_w= measured or calculated evaporation rate

Das et.al.(1971) used this definition for Ootacmund using potential evapotranspiration (PE) instead of E_w and the definition was modified as

$$CCGI = P/o.769\ PE \qquad \ldots(7)$$

Using the ratio of rainfall to CCGI value five different plant growth limits, considered to be indicative of varying water stress or excess conditions have been defined. On the basis of these limits four drought intensity classes were defined. Das & Mukerjee(1980) classified the country into various drought intensity classes using this concept for advocating necessary soil conservation measures. The steps involved in computations are given in Appendix-II

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 overestimated in certain cases. The Penman method was used for computation of PE. The values obtained by using CCGI values need further refinement.

2.5 Crop Parameters

Agriculture is the most sufferer of droughts as the ultimate affect of drought result in partial or total crop failure. Water deficit affects both crop growth and development directly or indirectly. The deleterious effects of the water deficits are usually more pronounced in tissues and organs which are in states of the most rapid growth and development. Therefore, water deficit should be avoided at such critical growth stages of crops. Area covered under the crops and the crop yields are also considered as the suitable crop parameters. The type of vegetation or crop is also one of the important parameters. Crop water requirement (i.e. consumptive use or evapotranspiration) depends on leaf area index (L.A.I., i.e. area of leaves per unit area of soil surface).

U.S. Weather Bureau defines drought as a period of dry weather of sufficient length and severity to cause at least partial crop failure. It is defined as a combination of temperature and precipitation over a period of several months leading to a substantial reduction in yield of one or more major food grains. Barger et.al.(1949; cited from W.M.O.1975a) evaluated precipitation climate from productive performance of crops.

Bali (1970; cited from Das & Mukerjee,1980) used the average rainfall limits with percent of cultivated area under rainfed cropping for classifying country's area under five drought intensity classes, viz., very high, high,medium, low and very low. Krishnan & Rao (cited from ; Krishnan,1979) illustrated the use of probability charts of rainfall for estimating the likeli-hood of droughts in respect of rainfed Jowar and Bajra crops at Jodhpur and Jaipur.

The severity of drought varies from region to region and crop to crop. Even for a given region the severity of drought may be different for different crops depending upon the drought resistance of crops. The lack of moisture at the critical crop growth states affects the yield drastically whereas at other stages if moisture deficiency occurs the reduction of crop yield may not be that significant. It is, therefore, needed to incorporate the physiological growth stages of crops in drought studies.

2.6 Hydrological Parameters

For better understanding of the drought, the classical hydrologic cycle may be considered which aptly describes the various phases of water regime. Precipitation, after it reaches the earth's surface, appears in several phases such as detention storage, surface runoff, infiltration, deep percolation, ground water storage, soil moisture storage evaporation evapotranspiration, cloud formation etc. If any of these phases is severly distorted, the water regime undergoes considerable changes. Soil is the store house of water from where plants extract moisture. The moisture stored is lost by the process of evapotranspiration. The actual soil moisture status governs the runoff and resulted streamflow. The moisture availability could be a better index of drought. Hence, the study of hydrological components like soil moisture, evapotranspiration and streamflows may prove to be better in quantification of droughts.

2.6.1 Soil moisture

Water in the soil profile is held with variable tensions and moisture held in between identified tensions are called different types of hydrological storages; i) Firstly, detention storage which is the amount of water held between field capacity and maximum water holding capacity. This volume of water find its way through the soil profile and gets absorbed by the soil profile or released into the channel system or ground water storage much after the rain, ii) secondly, the retention storage (i.e. available soil moisture) which is difference between permanent wilting point and field capacity. Water from through the process of evapotranspiration, iii) thirdly, the storage below permanent wilting point is, however, not generally available for any of the two purposes indicated above. The soil moisture availability is illustrated in Figure 4. Therefore, detention and retention storages are of special interests for study of hydrological and agricultural droughts.

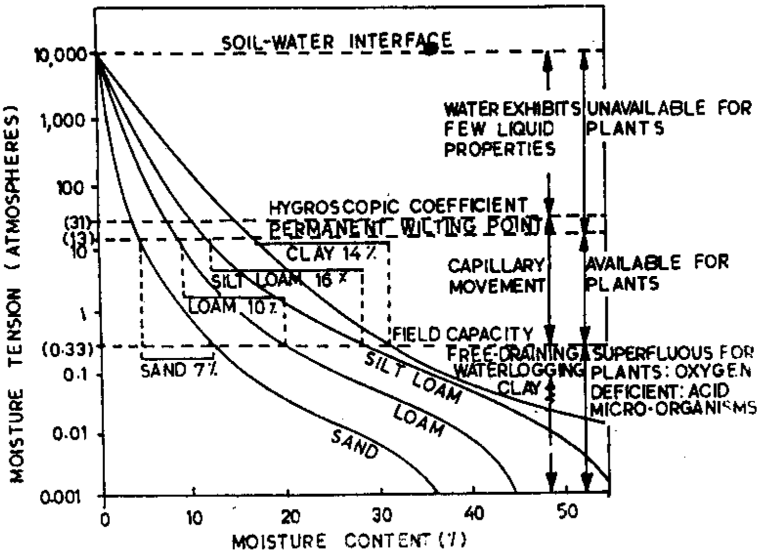

FIGURE 4 - RELATIONSHIP BETWEEN MOISTURE CONTENT AND MOISTURE TENSION IN FOUR DIFFERENT TYPES OF SOIL. INDICATING THE RANGE OF MOISTURE AVAILABLE FOR PLANTS (AFTER MORE, 1969).

Soil moisture measurement plays an important role in assessing the effects of drought severity and in assessing relationships to runoff and groundwater discharge. At very few places in India, soil moisture measurements are being carried out. The difficulty arises due to limited spatial representativeness of point measurements of soil moisture, and in the complex relationship between soil moisture, soil type, evapotranspiration, and soil moisture-ground water interactions. Most of the existing methods for determining soil moisture are based on computing the relevant variables from a set of other quantities, primarily climatological variables and physical soil characteristics.

The prime factor controlling the water balance of the plant-soil environment is the water supply available to plant which plant derives from the available soil moisture storage. Considering the basic water balance equation :

$$P = Q + U + E + \Delta W \qquad \ldots(8)$$

where,

P is the precipitation or irrigation water added,

Q is the runoff;

U is deep drainage passing beyond root zone;

E is actual evapotranspiration

W is change in soil-water storage

During drought condition, associated with extended rainless periods and in the absence of irrigation P,Q and U are zero. Therefore,

$E = -\Delta W$

The actual evapotranspiration depends on changes in soil water and is usually much less than potential evapotranspiration which may be very high under these conditions. This phase of the plant-soil-water relationship is quite complex and has been the subject of considerable investigation in recent years. Therefore, assessment of drought is very sensitive to soil moisture changes and evapotranspiration estimates

Van Bavel(1953; cited from Krishnan,1959) found that the amount of moisture deficit is quite sensitive to changes in moisture storage capacity of the soil. According to this study the average number of drought days decreased from 45 to 10 as the moisture storage capacity increased from 25 to 100 mm. Similar studies of agricultural droughts on the basis of daily moisture balance was made by Aired & Chen (1953),Van Bavel and Varlinden (1956), Pengra (1958), and Shaw(1963,1964) as cited from (Krishnan,1979 and WMO,1975a). In India few drought studies have been made by this method (Subrahmanyam, 1958 and 1964; Mehta,1968; Krishnan & Thavi,1969: Ramana Srinivasamurthy,1970 ; Krishnan,1971 etc.)

It has been demonstrated by Holmes & Robertson(1959; cited from WMO,1975a) that under non-irrigated conditions a water balance which takes into account soil moisture stress and plant rooting characteristics is superior to simple soil-moisture budgets not incorporating these features.

Garnder& Ehlig(1963; cited from Krishnan,1979) concluded that the root zone should be divided roughly into two moisture zones. The upper zone contains many roots and is depleted of water at a potential rate in proportion to remaining water in soil. The lower zone containing fewer roots is depleted of water at a much slower rate until most of the water in the upper layer is lost. Some research workers have noticed exponential relationship between evapotranspiration and soil moisture.

Baier & Robertson(1966) and Baier(1967) developed a versatile soil moisture budget for the estimation of daily soil moisture on a zone-by-zone basis from standard climatological data. This is typical of a number of methods which endeavour to make realistic assumptions regarding the extraction of soil moisture by plants and follows on form and modifies the earlier methods of Thornthwaite, Penman and Kohler. This method uses a climatological estimate of potential evapotranspiration as the upper limit of the actual transpiration and adjusts the later according to available soil moisture, runoff and drainage. It also subdivides the total available soil moisture into six ' Standard' zones of varying water holding capacities. It thus allows for the simultaneous withdrawal of moisture from different depths of the soil profile permeated by roots, in relation to the potential evapotranspiration, root concentration and available soil moisture in each zone. A feature of the model is the choice of different types of soil-drying curves, which makes it possible to test various concepts of the availability of soil moisture to plants in relation to soil and meteorological factors.

Figure 5 shows various proposals relating evapotranspiration to available soil moisture. A good agreement was found between the observed and estimated values using type C and E soil-drying curves. Over the whole range of the soil moisture cycle, statistical t-tests indicate that the use of type C relationship resulted in the best estimates, thus supporting to use of 'linear' relationship originally proposed by Th rnthwaite. However, when the available moisture content in the soil approaches zero even small errors in the estimates become important and could be corrected by adjusting the crop coefficients or by using a more efficient relationship such as type E.

Versatile soil moisture budget (VB) for estimating daily AE from changes in soil moisture per zone is given by

$$AE_i = \frac{K.S'_{(i-1)}}{S} Z.PE_i \quad \exp\left[-W\,(PE_i - \overline{\overline{PE}})\right] \quad \ldots(9)$$

where,

AE_i is actual evapotranspiration for day i(mm);
K is coefficient accounting for soil and plant characteristics for zone ;
$S'_{(i-1)}$ is available water capacity in zone at end of day i-1 (mm);

PE_i is potential evapotranspiration(mm) for day i(mm);

S is available water capacity in zone(mm);

Z is adjustment factor for different types of soil drying curves;

W is adjustment factor for effects of varying PE rates on AE/PE ratio;

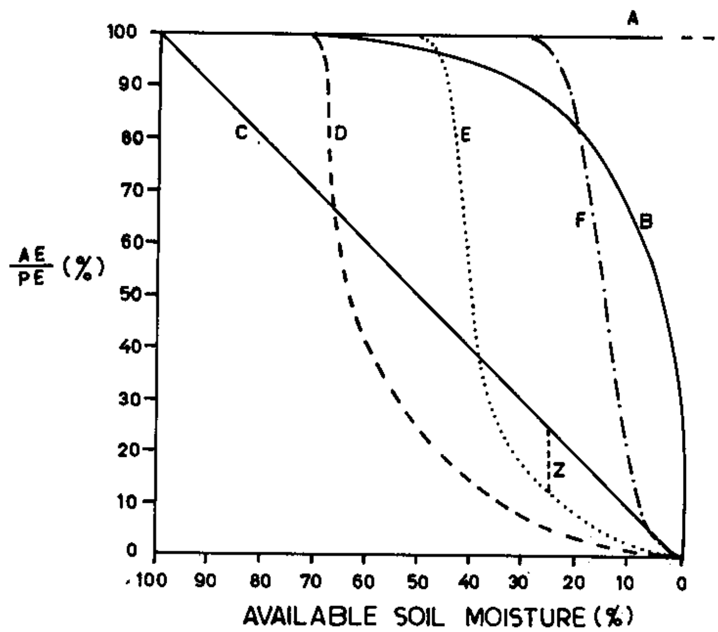

FIGURE 5 - VARIOUS PROPOSALS FOR THE RELATIONSHIPS BETWEEN AE/PE RATE AND AVAILABLE SOIL MOISTURE (AFTER BAIR & ROBERTSON,1966)

$\overline{PE}$ is average PE for month or season;

exp means exponent.

Sly (1970;cited from WMO,1975a) gave a climatic moisture index for soil climatic classification purposes.

$$I = \frac{P}{P + SM + IR} \times 100 \qquad \ldots(10)$$

where,

P is growing season precipitation

SM is soil water available to crops at beginning of growing season;

IR is calculated growing season irrigation requirement.

Burnash & Ferral(1973) studied the drought phenomenon in terms of the useful moisture availability in various storage elements e.g. shallow and deep root zones and streamflows and groundwater storage. A conceptual model consisting of four reservoirs, namely, the upper zone tension water storage, the upper zone free water storage, the lower zone tension water storage and the lower zone free water storage was proposed. The amount of water in each reservoir was than estimated by a hydrologic inventory technique which includes the various transfer mechanisms such as evapotranspiration, percolation, surface runoff, deep drainage, interflow, and base flow. The parameters were determined by inference from rainfall and discharge records. The approach is deterministic in a sense that it provides a transfer mechanism applied with actual or synthetic records of precipitation and streamflow for the calibration and focusses attention on moisture content as a measure of drought rather than on the absence of precipitation. But nevertheless, region actual-not potential-evapotranspiration could perhaps provide some better solution.

Bidwell (1973) proposed techniques for constructing and analysing models to simulate the relationship between hydrological drought and crop yields by means of production functions on the following type:

$$Y = f\ (x_1, x_2 \ldots\ldots\ldots\ldots x_n) \qquad \ldots(11)$$

where,

y is the yield at the end of growing season;

$x_1, x_2 \ldots\ldots\ldots x_n$ are functions or sets of the climatic and moisture supply variables for successive subperiods 1,2,.....n of the growing season

This function does not include the effects of variation in soil properties, use of fertilizers of or salinity on the crop yield. Bidwell proposed a general class of non-linear functions and a method of non-linear least squares to determine the unknown parameters for function f. He obtained the low explained variance which may be due to, i) not considering important variable e.g. evapotranspiration and ii) lack of data on crop behaviour.

Hillel(1977); cited from Sarma & Ravindranath,1980 and 1982) developed several models for calculation of evaporation ,and resulting soil moisture profile from a known initial non-uniform moisture distribution under varying conditions of temperature, crop cover, sinusoidal diuranal variation of potential evaporation and rainfall of fixed intensity over finite periods. Such studies, although very useful in providing more in sight into the problem at micro level, can not be easily extended to field conditions where limitations of data collection and non-uniform rainfall exists.

Sarma & Ravindranath (1980 & 1982) presented a generalised computer programme to study water balance in crop root zone. It computes soil moisture profiles from field observations of soil moisture tensions and evaluates the daily evapotranspiration and deep percolation losses. It takes care of the limitation in the availability of data due to occasional skipping of records for two or more days at a stretch. The programme includes the procedures for computation of infiltration and moisture flow. The programme is designed to handle data of tensiometer readings for a period of 95 days and for 7 depths. The input data needed are the daily rainfall, pan evaporation, tensiometer readings and soil moisture characteristics curves of tension versus moisture content and hydraulic conductivity versus moisture content. The programme has been listed by using field data of maize crop grown at IARI, New Delhi. The model needs to be tested for other soil types and crops.

Das (1982) proposed a soil moisture retention model for disposition of rainfall in context of flood and drought. Mass water balance model centering around variations in soil moisture has been offered. The model requires data on rainfall and mean temperature only besides the soil moisture estimation equation. The equations for field under four different management practices at Nilgiris were obtained with ESM(Effective soil moisture) as independent variate (Das et.al.,1967), having the form as,

$$SM = a + bx - cx^2 \quad \ldots(12)$$

where,

SM is soil moisture ;

a,b, and c are constants ;

x is ESM or API ;

API is antecedent precipitation index

However, ESM-SM equation is found to be more significant.

ESM factor is ratio of precipitation to square of mean temperature. Certain assumptions have been made for Nilgiris in arriving at the model, the model needs to be modified by incorporating a measured or determined component of surface runoff. According to this model, the management practice within the watershed, which offers high cumulative retention opportunity and also has least retention capacity indicating greatest dryness, is susceptible to droughts with slightest subnormal incidence of rainfall.

It has already been discussed that soil moisture storage controls the water balance of the plant soil environment and maintains the water supply available to plant. In most of the drought studies investigators have used Thornthwaite and Mather's book keeping procedure for water balance studies which assumes the available water capacity as 300 mm uniformly for all stations irrespective of soil type and other factors. Improved soil moisture budgeting models taking account of soil moisture stress & plant rooting characteristics would definitely prove to be superior under drought conditions. There is need of monitoring the soil moisture regimes using improved instrumentation techniques, developing models of soil water deficits and estimation of regional soil moisture deficit. Even the most practical water balance models ignore the details of infiltration process and assume that soil water storage is always replenished provided adequate water is available at the surface.

2.6.2 Evapotranspiration

As mentioned earlier, the stored moisture of the soil is utilised through the process of evapotranspiration. Evapotranspiration is the water loss from the earth's surface to the atmosphere which is the sum of evaporation losses from soil and water surfaces and transpiration losses from vegetation. The water loss taking place from an extensive vegetation cover under the ideal moisture, is termed as potential evapotranspiration(PE). Penman(1956) defined potential evapotranspiration as 'the amount of water transpired in unit time by a short green crop, completely shading the ground of uniform height and never short of water. Potential evapotranspiration is essentially determined by available heat energy(supplied by solar radiation, turbulent transfer from the atmosphere, or by conduction or radiation from the soil). It is necessary to distinguish between evapotranspiration under conditions of variable soil moisture and potential evapotranspiration.

The actual evapotranspiration (AE) is considerably influenced by the soil moisture supply, plant structure and physiological conditions of leaf and rooting depth etc. (Hagan and Vadia,1960; Slatyer,1963 and Slatyer & Denmead,1964; cited from Krishnan,1979). Just after rain or irrigation when the surface is visibly wet, the rate of evaporation is almost the same as from an exposed water surface receiving the same amount of the net radiation. But after the surface soil has dried, evaporation takes place from the deeper layers of the soil. There is a sharp and continuous decline depending on the length and complexity of internal diffusion pathway within the soil.

Further, when the plant grows in height and leaf area, the ground is shaded and consequently the evaporation from soil surface decreases and the plant transpiration rises progressively with increase in leaf area till the whole surface is effectively covered by the vegetation. Transpiration is insensitive to further leaf development and is maintained at a high level when the plant is actively growing. This period varies with the growth characteristics of the particular plant. It then declines as the plant matures. Another important effect of the plant on uptake of soil moisture is that as the roots develop, the plant has access to an increasing volume of soil water. As the available water declines, gradual reduction in transpiration occurs, becoming marked thereafter. At the soil moisture corresponding to the soil water suction of 15 atmospheres, plants begin to wilt. Evapotranspiration is an important parameter in water balance studies, particularly in the assessment of droughts.

Over the last 40 years number of methods of estimating evapotranspiration have been developed. In an attempt to evaluation of estimating methods, sixteen methods were selected by the technical committee on Irrigation Water Requirements of the ASCE(Irrigation and Drainage Division Report,ASCE,1973). The methods have been clssified as combination methods (Van Bavel-Businger,1966; Kohler et.al.1955; and Penman,1963), humidity methods (Ostromeck, Papadakis,1966 and Ivanov,1954) miscellaneous methods (Oliver;1961;Christinsen,1968; and Behanke Maxey,1969) , radiation methods (Jensen-Haise,1963; Stephense Wart,1963; Turc.1961; and Makkink,1957) and temperature methods Thornthwaite,1948 and Blaney-Criddle,1969).

Regarding the variation of evapotranspiration depending upon the available soil moisture,there are mixed opinions. Penman (Krishna,1979) found that the amount of water within the rooting zone plus 25 mm of water extracted from the soil below the root is available for transpiration at potential rate. After this amount is transpired, the transpiration rate decreases to about one tenth of this rate. Another group of workers (Thornthwaite & Mather,1955 and Denmead & Show,1962, cited from Krishnan,1979) believe in linear relationship betwween relative transpiration rate and available soil water.

Chang and Robinson (1963; cited from Krishnan 1979) indicated a curvilinear relationship between the ratio of actual to potential yield of Sugarcane to the soil moisture.

The curve was plotted between AE/PE ratio and actual to potential yield rates as shown in Figure 6. Assumption of linear relationship between AE/PE ratio and soil moisture only from 70% or 50% of the available moisture and full availability prior to that, has been found by number of investigators. Fitzpatrick (1967) and Krishnan & Kushwaha(1973; cited from Krishnan,1979) proposed similar models. Some investigators have obtained exponential relationship between evapotranspiration and soil moisture (Baier & Robertson,1966;cited from WMO,1975a).

In India, mostly the estimates of evapotranspiration have been made using Thornthwaite,Blaney-Criddle,Penman and modified Penman methods or using open Pan evaporation data. Crop coefficients have been also worked out by some investigators for certain crops and regions. Parasher and Singh(1963,cited from Krishnan,1969) for Delhi region, found that the ratio of consumptive use of water to Penman evaporation rose from 0.36 to 0.44 in early stages to unity during the period of maximum growth and fell to about 0.30 to 0.42 in the phase of maturity. Lysimetric studies in India are being conducted at various places, e.g., Delhi,Dehradun,Kota,Hyderabad,Ludhiana,Pantnagar, and other Places (IMD's stations) to study the evapotranspiration behaviour of different crops under varying moisture stress conditions. The studies indicate that as the crop matures, the pattern of evapotranspiration depends on crop physiology. It has been indicated by several workers(Venkataraman 1981 and others) that the ratio of evapotranspiration to Pan-evaporation increases after the crop starts growing and it reaches the peak at the critical growth stages of crops.

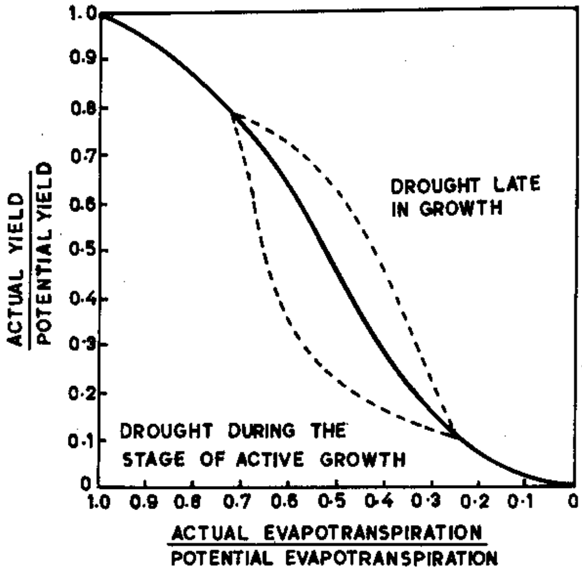

FIGURE 6 - EFFECT OF DROUGHT AT DIFFERENT GROWTH STAGES. (AFTER CHANG & ROBINSON, 1963)

Venkataraman (1981) obtained this ratio as high as 1.5 for Maize crop. The evapotranspiration may continue to remain as high as the potential rate or may be steady at a fixed fraction of PE rate, depending on the nature of crops (Sarker et. al.,1976 ; Subbarao et.al.,1976; and Venkataraman et.al.,1976) or may show a decline as in case of wheat. Gangopadhyaya et al.(1969; cited from Krishnan,1979) studied the variation of evapotranspiration/evaporation ratio for various stages of growth of wheat, sugarcane and cotton at Poona and indicated that peak demand of cotton and wheat was equal to pan-evaporation while of sugarcane was double of pan evaporation. The studies being conducted at Dehradun, Kota and Hyderabad on weighing type lysimeters also indicate that the ratio of evapotranspiration to evaporation is found to be higher during the active crop growth stages. Maximum evapotranspiration is observed at maximum leaf area index (Annual report, CSWCRTI,Dehradun,1981). Bhardwaj & Khullar (1982) indicated the increase of observed evapotranspiration of Maize crop upto 9th week and then its decrease till harvest, due to decrease in leaf area index.

Evapotranspiration is one of the important parameter of water-balance studies and it raises difficult problems, particularly in the assessment of drought, because of uncertain knowledge regarding the rate of loss during the soil moisture stress conditions (i.e. during the drying cycle of soil). It is the most sensitive parameter for drought analysis. A number of methods for estimating evapotranspiration are available, most of which give potential evapotranspiration, those which claim to give actual evapotranspiration are generally more complex, data intensive and unreliable. The estimates of drought quantification are quite sensitive to actual evapotranspiration.

Therefore, the correct assessment of actual evapotranspiration plays an important role in drought studies. There is need to develop evapotranspiration model taking into account crop factors (i.e. leaf area index, physiological growth stages etc.), soil water stress and climatic factors. It could be done by lysimetric studies. The relationship between actual ET and soil moisture is to be worked out for different soils and agro-climatic regions for better understanding of droughts.

2.6.3 Streamflow

Streamflow is one of the important hydrological parameters as it represents the runoff from a basin or catchment and determines the quantity of water available in various surface water resources. The precipitation deficiency is ultimately reflected in the resulted streamflow. Not only this, even the catchment characteristics, land use, vegetation etc. are also responsible for generated runoff. The drought phenomenon may be more readily studied from the hydrology of river basins for which local singularities are eliminated. The low stream flows are indicative of drought situations. When the flows are not sufficient enough to meet the required demand of water, it is considered that the drought has set in. Such studies may be more useful for long duration, wide spread large droughts occuring in more aerial extent. An objective definition of hydrological droughts as the deficiency in water supply on the earth's surface, or the deficiency in precipitation, effective precipitation (i.e. precipitation minus evaporation), runoff etc. based on theory of runs was advocated by Yevjevich (1967,1972) for stationary time series. For the univariate case and discrete time series of water supply, a selected arbitrary variable or truncation level x_o to represent the water demand was considered as shown in Figure 7. The discrete series truncated by this constant x_o gives two new truncated series of positive and negative deviations. A sequence of consecutive negative deviations proceeded and followed by positive deviations being called as negative run-length(n) is used to represent the duration of drought. The sum or integral of all negative deviations over such a run length is defined as the negative run-sum(D), and the ratio of the negative run-sum and negative run-length is called the negative run-intensity (D/n). The negative run-sum and run-intensity is associated with the severity of droughts. Yevjevich (1967) used area-runs as the basis for definition of continental droughts. Several theoretical and experimental studies of runs related to drought problems are available. The run-length has been more widely investigated by Liamors & Siddiqui (1969), Saldarriaga & Yevjevich (1970), Millan & Yevjevich(1971) and Salazar et al.(1975). The study of run-sums is very complex theoretically. only for the univariate independent normal process, the exact properties of run-sums were found by Downer et al.,1967 (cited from Norio tase,1976).

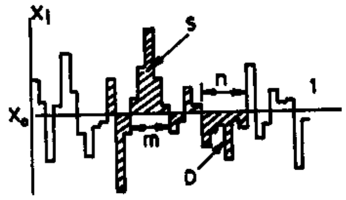

FIGURE 7(a)- DEFINITIONS OF POSITIVE RUN-LENGTH, m, POSITIVE RUN-SUM, S, NEGATIVE RUN-LENGTH, n, AND NEGATIVE RUN-SUM, D, FOR A DISCRETE SERIES X_i.......

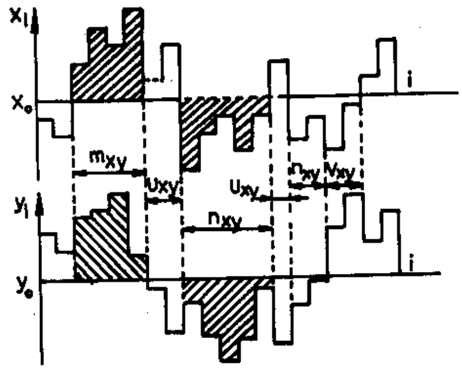

FIGURE 7(b)- DEFINITIONS OF JOINT RUN-LENGTHS OF A TWO-DIMENSIONAL PROCESS WITH TWO CONSTANT CROSSING LEVELS X_o and Y_o

The theory of runs has been applied to streamflow data, considering a suitable truncation level depending on the draft needs for agricultural or other uses by many investigators to study hydrological droughts.

The theory of runs cannot be used directly for the case of hydrological periodic- stochastic series as in the case of stationary stochastic processes, because of the periodicity involved.

Estimation of low stream flows is also a suitable way of quantifying droughts. Anand Prakash (1979) presented a deterministic model for estimation of the contribution of the irrigation return flow, rainfall, and upstream releases etc. for an affluent stream under drought conditions. Dracup et al. (1980) suggested a systematic approach to drought definition incorporating the use of theory of runs which requires the analysis to select the nature of water deficit to be suited, the averaging period used to discretize the raw data, the truncation level used to distinguish droughts from other events, and the regionalisation. Recently attempts have been made by Indian workers to investigate droughts on the basis of streamflows, but in a very limited extent. Verma (1979) proposed a non-linear storage routing equation in combination with base flow recessions to predict low flows for effluent steams.Parameters relating storage and outflow terms for the routing equation have been determined.He finally developed a physical model using these parameters and drought period for predicting low stream flows during droughts. However,this model was yet to be tested with actual field data.

Krishnamurthy & Ramasastri (1979) presented the case study of hydrological droughts in Mahanadi river basin upto Hirakud for the drought years 1962,1965,1966,1969,1972,1974, and 1976. Rainfall-runoff analysis indicated a decreasing trend of monsoon rainfall-runoff. No cyclicity could be established within the rainfall and runoff data.

Subhash Chander et al.(1979) proposed an approach to assess the magnitude and duration of droughts by means of statistical run analysis (advanced by Yevjevich et al.,1967) at critical levels in the time series using the concept of marginal probability distribution of successive events. A method of evaluation of these probabilities for a Markov process using T-function is evolved as an alternative to the existing cumbersome method of numerical integration using Tetrachoric series expansion. The authors suggested the use of Box-Cox transformation to make this methodology more conducive to a non-Gaussion distribution determined by the observed series. The concept and methodology have been illustrated using the flow data of Krishna and Godavari rivers. It was concluded that Godavari data is random, whereas, the Krishna river data is dependent.

2.7 Trends and Prediction of Droughts

Drought prediction is one of the intriguing problem of drought studies. It is important to analyse the drought severity, frequency and distribution. The severity of droughts may be measured by various parameters like deficiencies in rainfall and runoff, decline in soil moisture,reduction in ground water levels, and the storage required to meet prescribed drafts or demands. Since the droughts are the result of cumulative deficiency, records for individual days, months, and in some cases even years are not significant. A cumulative plotting of rainfall or a mass diagram of runoff, will show the effect of extended dry periods. In early days, practice was to find the most severe period recorded and design was then based on this single period. In recent years practice included, in addition to evaluation of extreme drought severity, estimates of the probability of occurrence of a drought of given severity and duration. The studies relating to the analysis of droughts on the basis of the characteristics of rainfall and streamflow, either through frequency analysis or through statistical/stochastic models and on the basis of synoptic treatment have been briefly reviewed here.

Deficiency of rainfall is often taken as the variable for drought prediction. Pinkayan (1966; cited from yevjevich et al., 1977) studied the probability or occurrence of wet and dry years using conditional probability distribution functions. Gibbs & Maher (1967; cited from WMO., 1975 b) analysed the past droughts in Australia in classifying the annual precipitation using the decile range. The first decile range is used to find return period of droughts covering a certain percentage of the continent. Even, the annual deciles of world deciles of world rainfall for the years 1960-70 have been computed and mapped. Chattfield in England (1966; cited from Subrahmanyam, 1967) in a mathematical treatment of rainfall data concluded that, the longer the spell (dry or wet) lasted, higher is the probability that, the following day would also be dry or wet. Downer et al. (1967) used run-lengths and run-sums to analyse annual rainfall data for drought studies.

In an attempt to study the sequences of dry days i.e. with less than 0.25 inch (Hershfield, 1970 and Hershfield et al., 1973) concluded that these sequences closely obey a geometric distribution, whose parameter can be obtained from number of precipitation days. The distribution of longest dry period was studied by Gupta et al. (1973) from a point rainfall process and the fit of observed and computed distribution was found to be rather poor. The first order Markov-Chain model has been mostly used for daily rainfall analysis.

Studies on the dynamic and synoptic treatment have been also employed in predicting droughts. According to Namias (1966; cited from Subrahmanyam, 1967) and Namias & Dorize (cited from Rodier and Beran, 1979) problem of drought is an integral part of the problem of atmospheric circulation. Beran (1979) discussed the problems of return period assessment and forecasting in light of alleged persistent periodic and fluctuating behaviour of the world climate. Closer analysis of annual time series suggested that persistence is largely confined to a tendency for dry year to follow dry year and to a slightly lesser extent for wet to follow wet. Sea surface temperature anomalies have been also often associated with droughts. Drought prediction has been also attempted by using the Sunspot cycles. Spectral analysis reveals no well defined cycles of rainfall anywhere but a wide spread irregular rhythm of two to three years is evidenced. The analysis at the same time does not preclude entirely the presence of a weak rhythm in the 11 to 13 year spectral band which might be identified with solar cycle.

It is generally agreed that the changes in oceanic and atmospheric circulations determine the outcome of climatological variables that result in droughts. But, relationships between drought characteristics and geophysical fluctuations in the eath's environment-whether atmospheric,oceanic, or continental, are very difficult to use in drought prediction. Climatic variables relevant to definitions of droughts still appear as random processes. Hence, major characteristics of droughts are best derived from available data on those variables which appear to cause or be associated with droughts.

It has been found that during the periods of deficient precipitation the deviation from normal conditions is greater for stream runoff than for rainfall (Chow,1964). In analysing the stream flow droughts, one of the simplest techniques is to construct a flow-duration curve for the given river or stream. But it neigher conveys idea of the sequence of flows nor of the duration of low-flow events. An alternative is to analyse the low flows over a given number of consecutive days and to estimate the recurrence interval of these events. This analysis is repeated for various periods of consecutive dry days to build up a series of curves as shown in Figure 8. Curves A to E show the flows for various duration periods for frequency or recurrence intervals of 50,20,10,4 and 2 years respectively. The

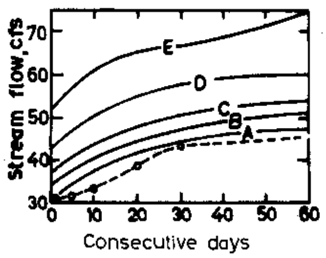

FIGURE 8(a)

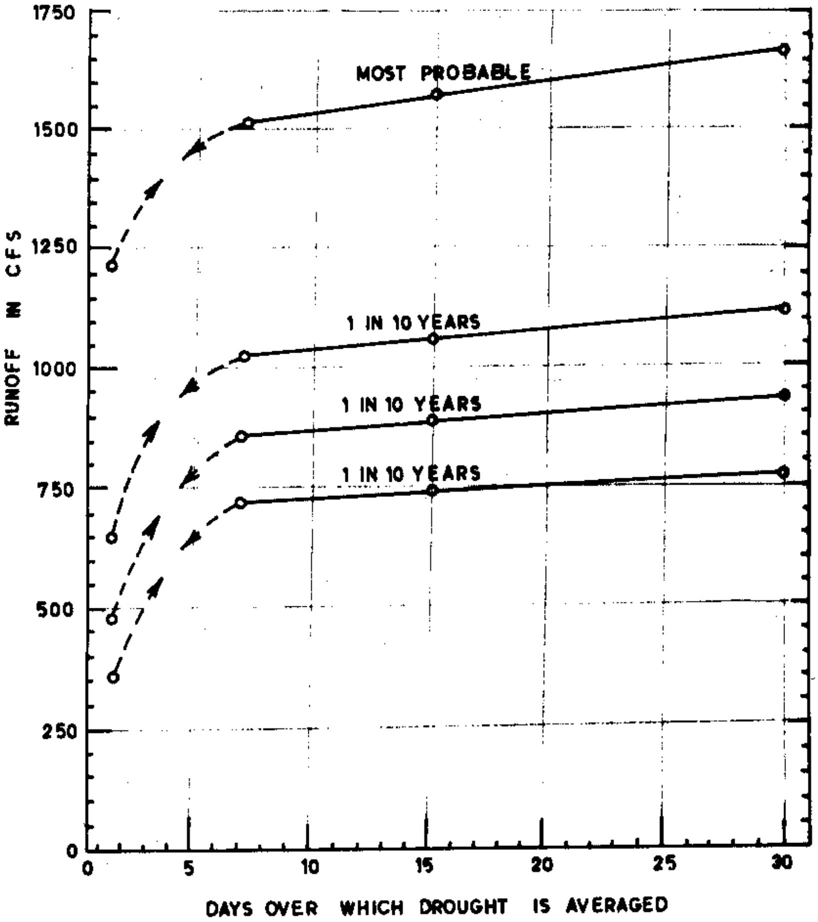

FIGURE 8(b)- FLOW DURATION CURVES FOR,8(a)FRANKSTOWN BRANCH,JUNIATA RIVER(CHOW,1964),8(b), ST.JOSEPH RIVER AT NILES(VELZ AND GANNON,1960).

dotted line represents the lowest average flow of record over various duration periods. Velz & Gannon(1960; cited from WMO 1975a) developed such curves for Michigam streams. Sometimes difficulty is encountered in frequency analysis of sequential events due to overlapping of data and repeated appearance of extreme values. This overlapping can be eliminated by the screening procedure. Another method is to use one of several frequency distributions to describe the probability of the magnitude of lowflows. The fact that many records of streamflow are too short to permit an extensive analysis has led to the development of methods of synthesizing data. One simple method is to establish relations between the short-period station and one that has been in existence for much longer.

In 1960s, the investigators started estimating drought streamflow frequency using statistical approaches. The investigators used the method of streamflow simulation also which treat discharge as a stochastic process. Stochastic modelling for stream flow simulation was first discussed in detail by Thomas & Fiering (1962; cited from James et.al.,1971) and later by Fiering (1967). Many of the studies of this type have been based on establishing the Markov property for the flows concerned, annual, monthly or daily. In some studies precipitation data as well as flow records have been employed in the simulation. These generation techniques have also been applied to the assessment of the period that is the most critical drought (Askew et.al.1971) for the system concerned. Huff and Changon(1964) developed a method of estimating drought streamflow frequency by using low precipitation frequency and a single geomorphic index, Whipple(1966), applied the station year method of regional frequency analysis to multi year hydrologic droughts, Yevjevich(1967) applied statistical theory of runs for drought analysis and Askew et.al.(1971) observed that existing synthetic streamflow generation models fail to accurately reproduce historical critical periods. Milan(1973) and salazar et al.(1975) presented methodology for computing the probability distribution of droughts based on run analysis The detailed statistical procedure in analysing the characteristics of the run-length and run-time are yet to be developed.

The hydrological data commonly used for drought frequency analysis is often subject to serial correlation.Yevjevich (cited from Beran,1979 b) found the average world wide value of lac one serial correlation close to 0.2 for annual runoff series. He indicated that lag-one serial correlation coefficient in excess of 0.2 will create a bias in inferred return period such that the estimated drought return period will be exaggerated.

Stochastic streamflow models attempt to preserve certain preselected statistical characteristics of the historical stream flows. Preservation of the 'Hurst phenomenon' as a measure of stochastic dependence in stream flows is considered to be an important measure. Hurst (19651) (cited from Dawdy et al.,1979) found that the statistic R/σ, where R is the range of cumulative departures from the mean of the sequence and σ is the standard deviation, was a power function of the length of record used to estimate R and σ.

$$R/\sigma = \left(\frac{N}{2} \right)^H \qquad \ldots(13)$$

Where N is the length of the series and H is known as the 'Hurst coefficient'. Hurst obtained a range of H from 0.46 to 0.96 for various geophycisal time series. The mean value of series examined by Hurst was 0.72.

Initially, the first order autoregressive AR(1) model was used, but it was found that extreme droughts in general could not be modelled by means of AR(1) models. Fractional Gaussian Noise (FGN) model introduced in late 1960s could preserve the Hurst phenomeon. In 1971, O'Connell showed that the first order auto regressive moving average ARMA(1,1) model could do so, as an approximation to FGN Model. An alternative method developed to preserve this phenomenon was the borken line process BLP(Rodrignez-Iturble et al,1972 and Mejia,1972; cited from James et.al,1981).

In an attempt to compare the stochastic streamflow generation models, James et al.(1981) found that the ARMA-Markov and ARMA models are the best overall models in terms of preserving short and long term persistence of the stream flow sequences (i.e. lag-one autocorrlation and Hurst coefficients) The broken line model was judged to be the best in terms of minimising the economic regret as determined by an agricultural crop production function.

Dawdy et.al.(1979) stressed the need of physically based stochastic models (based on Cause effect relationships i.e. physical mechanisms) rather than statistically based models aiming purely at preserving certain statistical properties alone. They have advocated the possibility of using conceptual tank model for streamflow modelling od droughts. The tank model, originally developed by Sugawara (1961) have been used for deterministic modelling(Sugawara,1967;Sugawara,Ozaki,Wantanbe and Kastsuyama,1974;Sugawa4a,Ozaki,Wantnabe and Katsuyama,1976) and stochastic streamflow modelling(Pegram,1977;Selvalingam,1977)as reported by Dawdy,et.al.(1979).

Tank model consists of a number of tanks placed vertically,horizontally or both depending on morphological characteristics of the catchment. Each tank has one side and one bottom outlet, excepting the top tank provided with two or more side outlets. This, the tank model represents zonal structure of waterflow. The sum of outputs obtained through the side outlets makes the computed discharge. The model structure can,therefore account for the non-linear character of the runoff phenomenon through a complex linear system. The multiple orifices can lead to piece-wise linearisation to a non-linear response. Initial abstractions and the effect of antecedent soil moisture conditions can also be properly accounted for. The main draw bac of the model appears to be the parameter estimation that is by trial and error method. The 4 x 4 tank model for non-humid basins may be used for low stream modelling. The tank model retains a reasonable degree of physical realism. The model needs the daily rainfall, streamflow and evapotranspiration data.

The probability distributions of monthly catchment soil water deficits using rainfall and evaporation data have been used for forecasting droughts by Cordery(1981). In this model soil water deficit(SWD) is the difference between the actual water storage and the maximum storage that can be sustained (i.e. field capacity) and the drought is assumed to occur when there is a large value of SWD. It is assumed that there are parts of all catchments e.g. outcropping rock, swamps or waterlogged areas which have no soil water storage capacity & that any precipitation on these areas runs off immediately. It is also assumed that when the catchment is fairly wet(SWD morethan-10 mm), a large proportion of precipitation would runoff than that directly indicated by the SWD, since low SWD would indicate that significant part of the catchment surface is saturated. To obtain the SWD for the catchment, the model is run separately to obtain the SWD for each root zone capacity area and then the catchment weighted average SWD is obtained. Evapotranspiration loss as 70 percent of the pan evaporation was considered in calibrating the model. While using the model,say, if January SWD is fixed at some value, the rainfalls observed in February each year could be input to the model to determine the resulting distribution of February SWDs, given the January,SWD value and so on.

National Commission on Agriculture(1976) and Pisharoty (1978) indicated that there are no systematic trends, and that the rainfall variations have been practically stochastic. Power spectrum analysis have shown several peaks with several periodicity but they have been found to be of no forecasting value. NCA(1976), and Krishnan(1979) reported that the spectral analysis of Palmer's drought indices by Rao et.al. (1971) indicated some relation to quasi-biennial and eleven years sun spot cycles in some areas. The amplitude of the cycle being, however, too small to be of significance.Victor&

Sastri (1979) analysed the dry spell probability using Markov chain model (first order) applied to daily rainfall data of monsoon months to evaluate conditional probabilities and length of dry spells at different cumulative probability levels during growth stages of bajra crop in Delhi.

Ashok Raj (1979) presented a computer based forcasting model (main programme MONSOON and two sub-routines RAIN 1 and RAIN 2) for rainfall frequency and probability analysis of critical dry spells. Ramasastry (1979) also studied the trends of rainfall in West Rajasthan and concluded that there is no sign of decreasing trend of rainfall in West Rajasthan. Verma (1979) presented aphysical model coupling base flow recession with non-linear storage routing to predict low flows in effluent streams. Prediction of hydrologic characteristics of droughts was studied by Subhash Chander et.al.1979). Theoretical analysis by means of theory of runs at critical levels in time series for the estimation of the probabilities both for the independent and dependent normal series has been presented. The analysis is supported by two case studies of Krishna and Godavari rivers. The results obtained are encouraging.

It appears that in India mainly the statistical analysis of rainfall has been attempted to predict the occurrence droughts that too with no definite trends. Very limited studies have been done to predict the droughts on the basis of low streamflow analysis. More attention has been given to streamflow modelling for high flows rather than low flows. There is need to develop models for low streamflows taking into consideration catchment characteristics also. It has been realised that major component of the drought phenomenon is unpredictable and has to be dealt through probability analysis of hydrological aspects like rainfall, soil moisture, stream flow, ground water depletion etc.

3.0 EVALUATION OF DROUGHT IMPACTS

3.1 General

Droughts may be considered as having long-term and short-term impacts. Short term effects are generally known if not adequately understood. Dryland agriculture is often first to experience the direct effect of drought, usually in terms of reduced yields and dust blowing from dry,bare fields. Recurrent droughts result in low stream flows, reduced reservoir levels and ground water levels and thus making irrigated agriculture also to suffer. It brings in short water supplies for domestic usage, low power generation due to reduced reservoir levels and problems of insanitation etc. Besides there are several indirect impacts on the community.

Long term effects of drought are rather more subtle and difficult to assess, but it is reasonable to assert that their magnitudes could exceed short term effects. If a flood follows a drought, more damage can occur because runoff is more rapid and causes greather volumes of debris. Long term persistent droughts even impair the ecological balance of the region and accelerate the process of desertification also.

3.2. Review of Techniques

Consequences of droughts on crop yields, depletion of vegetation, overgrazing, land use pattern, desertification water regime, river morphology, socio-economic conditions etc. have been noticed continuous record of water levels in reservoirs, groundwater storage and streamflow provides a base for evaluating the impact of drought on water regime. Some have tried economic models for evaluating drought impacts Very limited studies have been made to study the effect of drought on water quality and river morphology. Some of the available research findings and techniques/ models, to evaluate drought impacts have been highlighted.

3.2.1 Consequences of droughts on crop yields morphology and land regime

It is apparent that during low rainfall years the yield of crops are below normal (Table 2, after Krishnan et al.1977). It has also been observed that even during a normal/surplus rainfall year, short period droughts occur which reduce the crop yields. In spite of introduction of improved agricultural technology, the considerably reduced yield of food grains in India has been observed during the drought years 1965-66,1966-67,1972-73 and 1974-75, as evident from the Table 3(Government of India,1976). Many direct methods could be employed to estimate the effect of drought on crop yield by crop cutting survey and comparing the yield with that the yield of a good year. Knowing the rate of moisture supply (rainfall) with respect to time, crop production function models could also be used to evaluate the drought impact on crop yield.

Krishnan(1977), Saxena(1977), Shankarnarayan(1977),

Table 2. Annual S.W.Monsoon Rainfall and Actual Evapotranspiration During Growing Season and Yields of Bajra and Kharif Pulses in Jodhpur District(After Krishnan, 1977)

Year	Annual rainfall (mm)	S.W.Monsoon rainfall (mm)	Actual Evapotranspiration during growing season (mm)	Yield in Kg/ha	
				Bajra	Kharif/ pulses
1951-	330	237	249	45	40
1952	440	309	317	164	159
1953	403	301	389	356	463
1954	398	288	292	119	651
1955+	367	287	301	110	459
1956+	581	344	434	86	442
1957-	312	167	226	227	341
1958	365	180	283	87	325
1959+	350	234	282	213	143
1960-	135	176	128	56	202
1961+	384	266	238	201	437
1962	322	301	291	173	324
1963-	179	144	173	47	134
1964+	541	361	294	141	157
1965-	248	251	282	123	126
1966	269	290	347	150	111
1967	529	250	425	233	241
1968-	179	143	141	12	9
1969-	93	136	137	34	25
1970+	595	399	425	528	295
1971	308	226	239	232	126
1972	359	138	176	24	24

\- deficit year
\+ surplus year

Table 3. Food Grain Production (in 1000 tons) from 1963-64 to 1975-76

Year	1963-64	1964-65	1965-66	1966-67	1967-68
Production	80642	89356	72347	74231	95052

Year	1968-69	1969-70	1970-71	1971-72	1972-73
Production	94013	99501	108422	105168	97026

Year	1973-74	1974-75	1975-76
Production	104665	99826	120833

Source: Govt. of India (1976)

Mannn(1977) and Bharara(1978) reported low yields of agricultural crops, depletion of vegetation and overgrazing, decline of permanent pastures and fallow lands. Barren cultivable and uncultivable wastelands, permanent pasutres and fallow lands declined by 16.8 and 6.95 percent respectively, during the period 1951 to 1971 (Mann et.al,1977 ; cited from Mann, 1979). There has been a significant decrease in grazing lands due to extension of cultivation in marginal lands, resulting in overgrazing of the diminishing grass lands.

Most of the dust storms in the Indian desert occur in May and June. In Jodhpur region, the frequency of dust hazes and storms was found to be much more druing 1969-70, and these were the years subsequent to the severe drought years. It has been observed that drought years result in sparse vegetation in the semi-arid and arid zones, which with biotic interference deteriorates fast and creates bare sandy patches and allow the soil to be blown off more vigorously. This wind erosion results in the occurrence of larger number of dust storms and dust hazes in the subsequent year, particularly in the windier months of May to June. During the period 1951 to 1972, there was an increasing trend of dust storms, whereas rainfall showed a decreasing trend. It is evident that whenever the rainfall decreases steeply, in the year subsequent to it there is a sharp rise in occurrence of dust storm(Figure 9 after Krishnan 1979). Thus the incidence of drought has a multiplier effect on desertification.

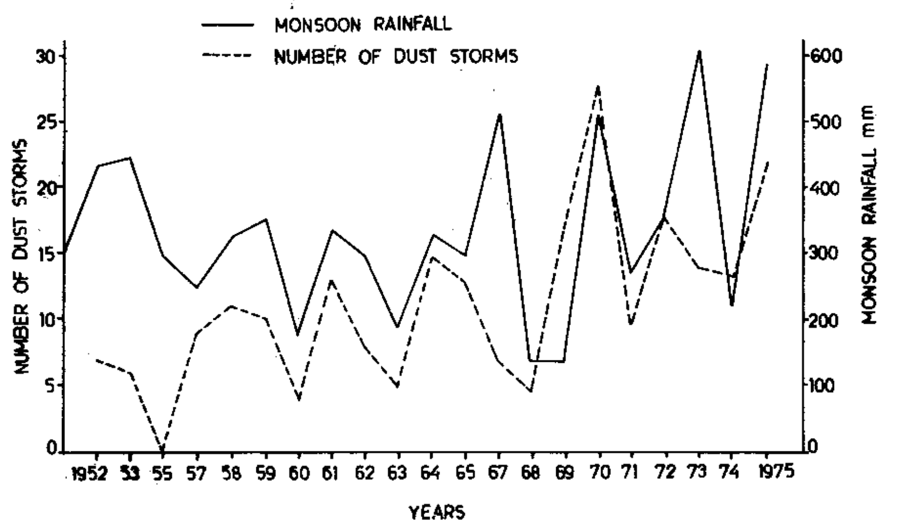

FIGURE 9- RELATIONSHIP BETWEEN FREQUENCY OF DUST STORMS AND MONSOON RAINFALL
(AFTER KRISHNAN 1979)

Drought influence morphology of streams in addition to the reduction of base flow. The sediment carrying capacity of the stream is reduced considerably, resulting in agradation along the length of stream. This results in changes of channel dimensions. Garde et.al.(1979) studied the effects of droughts on river morphology and they also supported that as a result of protracted droughts, the reduced vegetal cover will enhance sediment loads and surface runoff into the rivers during the post-drought floods, affecting the equilibrium in the river.

The impact of drought on ecosystem units (vegetation, plant life, agriculture, water, environment etc.) can help in identifying and predicting droughts and adopting corrective measures. Remote sensing, in the form of repetitive satellite imageries could be one of the possible means for such studies. An attempt in this direction has been made by Chkaraborthy & Roy (1979).

A comprehensive model was presented by Milan(1972,1973) to evaluate the impact of drought on the regional economy. The model permits accounting for the direct and indirect effect of droughts in both space and time. The input output or inter industry analysis has been used for regional water resources planning by Lofting (1963 and 1968), Bargur (1964), Miernyk (1969), Gray(1970), Turner(1970) Schaake(1971) and others as cited from Milan(1972). He also considered dynamic type interindustry model to simulate regional economy. Milan considered the problem of maximising the total income for a region in a given period, that is finding the objective function :

$$\text{Max} \sum_{i=1}^{n} C_i \; X_i \qquad \ldots(14)$$

where,

C_i , is the income coefficient for the ith sector among the n sectors of the economy under consideration and

X_i , the output of that sector.

Milan assumed the occurrence of drought to be random rather than a deterministic phenomenon and modelled the drought statistically as a time series in terms of water availabilities over a so called time horizon. This model then served as input of the dynamic model of the regional economy. Monte Carlo method of generating large numbers of hydrologic samples was used to make probabilistic statements about the different impacts of droughts.

3.2.2 Effect of drought on groundwater

The studies conducted at number of places indicate that the occurrence of severe droughts does affect groundwater. The main source of ground water recharge is rainfall and return flow from irrigation in canal irrigated areas. The response of groundwater levels to droughts is illustrated in Figure 10 for the Santa Ana Valley in California (cited from Chow, 1964). The figure illustrates the correlation between stream-

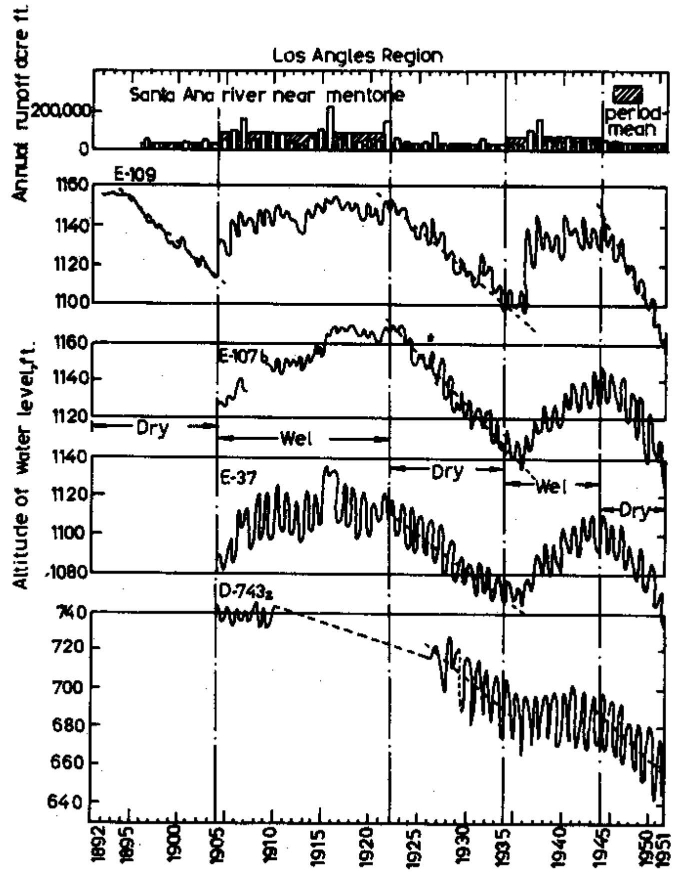

FIGURE 10 - ANNUAL RUNOFF OF THE SANTA ANA RIVER AND ALTITUDE OF GROUND WATER AT SELECTED WELLS IN THE UPPER SANTA ANA VALLEY (FROM CHOW, 1964).

flow, groundwater levels, and long-term climatic fluctuation, as well as an apparent progressive overdraft of water. Because of the size of under groundwater storage, the depletion of groundwater reservoirs during a single drought is not common. But, in case of recurrent severe droughts depletion, may occur when draft rates greatly exceed recharge or where the groundwater reservoir is relatively shallow.

A very little information is available about the rainfall recharge to groundwater. The recharge value of course would vary from one terrain to another depending upon the rainfall intensity and distribution, terrain characteristics etc. The studies conducted in the arid zones of Western Rajasthan by Chatterjee(1978) and Chatterjee et.al (1979) indicate that even for a drought year preceeded by a flood year, the groundwater storage does not meet the requirements of the area. Variation in static water level during pre and post monsoon period has been observed as 0.8 m and annual recharge to aquifer works out to 28.8 mcm (million cubic meter) of which 11.52 mcm are recoverable. The average annual rainfall of this region is 528.0 mcm during normal years. It clearly indicates that the recharge is definitely low. In the central Maharashtra where the area is occupied by Deccantrap and average rainfall is 400 to 500 mm, it has been estimated on the basis of seasonal water level fluctuations that about 10% of the rainfall is added annually to groundwater reservoir (Singhal,1979). Sharma et al.(1982) estimated by using hydrodynamic approach that ground water recharge in plain areas of the Visakhapatnam basin comes to about 35% of the total precipitation.

The rainfall being the main source of groundwater recharge, any violent fluctuation of rainfall as observed during recurring drought periods certainly lowers the ground water levels. Moreover, groundwater happens to be one of the main sources of irrigation in these drought stricken areas. Nearly 45% of the area in the arid zone of Western Rajasthan is irrigated by ground water resources. Same is the case in other areas also. Due to the absence of major surface water resources and recurrence of drought, the inhabitants of these regions have to depend on the exploitation of ground water resources for irrigation and domestic water supply. Utilisation of ground water has been found directly related to the drought year which is very much evident from the increasing trend in number of wells in use. Though the groundwater is replenishable in nature, its excessive development results in decline of water table. When the mean long term draft exceeds mean annual recharge in any basin, ground water mining takes place necessitating planning for various artificial recharge measures. Malik and Banerjee (1979) studied the influence of drought on groundwater storage particularly in shallow, unconfined aquifers and proposed an exponential decay function to identify recession characteristics of the aquifer which can be used to predict groundwater levels under future drought conditions. Equation used is

$$h = h_o e^{-dt} \quad ...(15)$$

where,

h_o is initial height of W.T. above m.s.l. and

h is the height of W.T. after time t above m.s.l.

Procedures for estimating the recession parameter under various conditions of ground water discharge(i.e. pumping etc.) have been proposed. Though, they have used simple Dupuit's assumption which may not be that accurate as compared to latest developed techniques, but for easy solution of field problems this approach may be reasonable.

The effect of drought on various groundwater basins should be ascertained in advance. The occurrence of drought not only affects the groundwater quantity but quality too e.g. increase in groundwater salinity. In a study Chatterjee (1978) indicated that nearly 65% of the arid region of Rajasthan is having groundwater with total soluble salt of over 3000 ppm. The continued use of these waters renders the soil saline or saline/sodic. In a study, Singh & Kumar (1979) also reported the increased salinity and alkalinity levels in the drought prone areas where the irrigation water is very limited.

Walling & Poster (1979) reported the unprecedented increase in the nitrate concentration in the streamflows of three catchments in England. The increase in level due to single severe drought was found to be about 3 to 9 times of the safety levels.

3.2.3 Consequences of droughts on socio-economic aspects

The impact of drought has a number of socio-economic aspects also. Due to scarcity of food grains, water, fodder, and all such items during the drought years, a very large number of men and animals migrate to other places to meet their needs. It creates severe degradation of vegetation and social problems. A case study made by Bharara (1978) to study socio-economic consequences of drought indicated that during migration the human and live-stock populations encounter serious hardships and a large number of families fall under perpetual debts and land attachments and are adversely affected by agrarian disturbances. The incidence of drought in an area with higher population density would do more harm than the same in an area of lesser population density. A society having a wide economic base is affected by this natural calamity to a lesser extent than a society having a limited resources base.

4.0 DROUGHT CONTROL MEASURES

4.1 General Control Measures

The dependence of India's agriculture on the Southwest monsoon and its consequent vulnerability has brought to focuss the crucial role of water resources development, conservation and utilisation vis-a-vis land development also. The comprehensive strategy required for the development, conservation and utilisation of water resources is governed by the many interlinked factors like water availability (surface or groundwater), its quality, location, distribution and variation in its occurrence, climatic conditions, soil type, competing demands (agricultural/non-agricultural), land use system and socio-economic conditions. Our aim,therefore, is to increase the production per unit volume of water per unit area of cropped land per unit time.

The drought control measures may be divided into two broad classes:

i) Supply oriented measures, and

ii) Demand oriented measures

The supply oriented drought control measures include.

1. Operational methods of surface reservoirs that is, using special storage spaces exclusively for drought needs, better selection of operational rules anticipating future needs etc. The research has been carried out by number of workers

in other developed countries using various criteria and constraints on reservoir operation. Several optimization models are there but there is no specific model to deal with drought conditions;

2. Effective utilisation of ground water storage reservoirs including recharging ;

3. Interbasin or Intrabasin water transfers ;

4. Conjunctive use of surface and ground water

5. Improving conveyance efficiency of the conveyance structures by minimising the on way losses, by lining the system.

6. Use of soil conservation measures for increased water yield.

7. Rainfed agriculture management by improved varieties and agronomic practices ;

8. Runoff harvesting structures ;

9. Increasing soil intake and soil water storage ; and

10. Improved methods of irrigation etc.

The demand oriented drought control measures include:

1. Land use regulation to minimise water use during droughts for example changing over from traditionally agriculture to pasture or grass land;

2. Demand reduction strategies, for example changing crops and cropping practices,domestic water use etc; and

3. Improved water conservation practices.

The technique of sub-surface moisture barrier as means of improving moisture storage in sandy soils by placing bentonite clay and plastic films to a depth of 60-70 cm in soil was advocated by Erickson et.al.(1968 ; cited from Singh,1978). Later they preferred to use liquid asphalts as moisture barrier. Singh(1978) reported that the new technique using bentonite and as phalt barriers gave satisfactory results. The researh is reported to be in progress.

Water harvesting techniques being used in Australia as reported by Hollick (1978) are more or less the same as have already been mentioned.

In India, similar studies have been conducted by various Institutes of ICAR and regional centres at different locations, Agricultural Universities, Irrigation Research Institutes, and ICRISAT. The general recommendations have been summarised below.

- Harvesting and collecting rainwater from adjoining hills as being practiced in dry areas of the country by constructing embankments or digging ponds or by making an artificial micro-catchments as done by ICRISAT at Hyderabad. The stored water may be recycled for supplemental irrigation to act as life saving irrigation when applied at critical growth stages of crops.

- Construction of percolation tanks and nalla bunds in the semi-arid and arid regions for ground water recharging.

The effectivenss of these structures has been reported by Singhal (1979),Rao (1979), Hatwalne(1980) and many others for Maharashtra and Andhra Pradesh region and the same is true in areas of Haryana and Rajasthan adjoining Aravali ranges.

- Practice of contour bunding for low rainfall areas having permeable soils, graded bunding for relatively high rainfall areas or areas having relatively impervious soils, conservation ditching in black cotton soils of Karnataka, conservation bench terrace and broad beds and furrows (as developed by ICRISAT).

- Use of sealants like soil + cowdung + straw mixture, asphalt, bitumen etc. Dhruvanarayana and Kamra(1980) recommended the use of alkali soils or soidum carbonate as a sealant for farm ponds etc.

- Patnaik (1981) suggested a 3-phased approach of on-farm runoff management for Karnataka comprising of measures at inter-terrace level, at terrace level, and at farm level(i.e. Ponds etc.).

Considerable amount of research has been done in the past and is being done to evolve different strategies to combat the affects of droughts in arid, semi-arid and sub-humid regions of the world. The control measures of varying types ranging from water harvesting to improved package of practices for different crops under varying locations have been evolved to suit to location specific problems. On the basis of past research findings, strategies can be enumerated as below on the recommendations of the working group report of N.C.A.(1975)

- Conserving and storing water in-situ ;
- Water harvesting and recyling in extremely dry areas ;
- Increased efficiency in the conveyance and distribution of water using efficient methods of water application ;
- Growing of crops and varieties in relation to climate and weather ;
- Suitable agronomic practices for aberrant weather ;
- Flexibility, in ratio of Kharif to rabi crops;
- Drainage of excess water (if any) to bring in proper soil physical and chemical properties ;
- Silvy-pastoral systems in the dry areas;

The various promising technologies developed in the world by various investigators for arid zones have been reported in publication of National Academy of Sciences, Washington, D.C.(1974). The important practices have been listed, here,

- Rainwater harvesting, by collection rainwater from hill slopes, man-made catchment treating soils with chemicals or covering it by polythene sheets etc.
- Runoff agriculture, involves in situ moisture conservation where water is used directly by the crops-e.g. interrow water harvesting, water spreading dikes, contour farming etc.,
- Re-use of waste water for ground water recharge irrigation etc.
- Ground water mining
- Reducing evaporation from water surfaces using liquid chemicals e.g. cetylalcohol,wax and providing sand-

filled storage dam with well shaft behind the dam ;

- Reducing seepage losses in canals and ponds etc. using sealants like chemicals, plastic sheets, asphalt, ferrocement and lining.
- Reducing evaporation from soil surfaces using plant residue, gravel mulches, plastic mulches, chemicals etc.;
- Water saving irrigation methods like trickle or Drip sprinkler irrigation, Pitcher irrigation etc ;
- Using standard irrigation scheduling procedures.
- Use of short duration, high-yielding, deep rooted varieties of crops with a good degree of stability to with stand dry climatic conditions;
- Improved agronomic practices like cover crops, surface mulching, legumes, strip cropping, contour farming, intercropping and mixed cropping with one short and other deep rooted crop;
- In the dry regions (either on account of low rainfall or limited soil depth), grasses and trees can be established profitable. The tree species suitable for storage, small timber, fuel or fodder may be planted.
- Agro forestry practices i.e. growing of fast growing less spreading type of trees around the field boundaries or other wasted farm land. It would reduce the descicating effect of hot winds on the crop.

Apart from these,there are many drought relief programs like food for work, etc. which have been put into implementation during the past droughts.

Watersheds approach, though its concept is not new, is being advocated for planning and management in drought-prone areas for integrated area development. Three distinct types of tasks need to be performed for the development of these areas (Jaiswal,1981): i) Integrated watershed programme for the optimum use of land and water (i.e. long term measures); ii) short gestation socio-economic development programme(i.e. generating employment opportunities); and iii) Disaster management in the event of drought occurrence (i.e. action plan ensuring availability of food grains and drinking water, relief measures like food for work etc.). Looking at the urgency of the problem, Indian council of Agricultural Research and its Institutes have selected number of watersheds and micro watersheds in different drought prone areas of the country for planning and execution as operational research projects. The results of the already executed works at ORP Sukhomajari (Haryana),G.R.Halli (Karnataka) and other places by C.S. and W.C.R. & I.I. & its centres have been promising in this regard. The strategy involves detailed planning of crop production, water harvesting, agro-forestry, pasture development etc. on ' Watershed' basis.

The International conference on ' Rainwater cistern systems, held at Hawaii, in June 1982 brought to focuss the effective use of runoff harvesting from roof-tops. Gupta & Katyar(1982) presented the scope and utilisation of rain water cistern systems for the Himalayan Region of India. The emphasis may be given to harvest runoff from roof tops, roads and other such built up areas in drought prone areas.

4.2 Artificial Recharging of Ground Water

It has been already discussed in the earlier chapter that the rainfall is the main source of recharge to groundwater and during the drought period , low and erratic distribution of rainfall and the increased dependence on groundwater exploitation for various uses result in decline of water table. The only alternative is to replenish the groundwater by some artificial means (i.e. recharging). Artificial recharging is normally defined as augmenting the natural infiltration into underground formations by some method of construction, spreading of water or by artificially changing natural conditions. It may be incidental or deliberate. Soil conservation practices in addition to conserving soil, aid in reduction of surface runoff and maintain the infiltration capacity of soils and thus augment groundwater recharge. There are many methods of artificial recharge such as water spreading, flooding and basin methods, artificial recharge through wells, pits and shafts and induced recharge.

Construction of percolation tanks and check dams across the nallas and water courses are considered to be quite suitable for artificial recharging under the conditions prevailing in many parts of the country e.g. Maharashtra,Andhra Pradesh, Karnataka, Rajasthan,Haryana etc. This most commonly used method not only acts as percolation basin but also checks erosion during flash floods and keeps the drought at bay. A percolation tank is a small tank whose capacity generally ranges from 0.142 mcm to 0.566 mcm (5 cm cft to 20 m cft) and constructed by means of an earthen bund across a river or stream or nalla. Storage strcutures upto 2 m cft capacity are called Nala bunds or percolation ponds which are normally executed by the Agricultural Department as being practised in Andhra Pradesh (Subrahmanyam & Rao,1982). The site investigation from geohydrological view point is necessary for location of such tanks.

In past during the drought year 1971-73 large number of percolation tanks have been constructed in some drought prone areas of Maharashtra, Andhra Pradesh,Rajasthan etc., But as on today, very little information is available about the rate of recharge and area of influence under these tanks. In an attempt to determine the recharge from percolation tanks in basaltic formations of central Maharashtra,Ral (1975) found that the average area of influence under a tank is about 1.5 sq.km., the average groundwater level rise is about 2.5 m and annual artificial recharge to groundwater from each tank is about 15 ha-m. In a more detailed survey of seven tanks with an average storage capacity of 0.13 mcm,Rao (1979) found that 1) the area of influence of tanks on the averae is 1.7 sq.km., 2) the rise of groundwater level is about 2.5 m; and 3) the recharge to groundwater varies from 0.032 mcm to 0.113 mcm with a mean of 0.079 mcm; which is about 60% of the tank capacity. This additional water could be utilised for beneficial uses by constructing 6 new wells of 0.012 mcm each. The rise of water level was generally found to be more in wells nearer the tank and the same gradually reducing away from the tanks.

Percolation tanks are definitely quite effective in ground water recharging provided these are located at favourable sites. It is considered that the wells should have a minimum recuperation rate of 0.0014 cm-m/sec for the sites to be recommended for construction of percolation tanks. The effective influence zone should be delineated subsequently during detailed hydrological investigations. The groundwater development in these areas is mainly by dug wells. However, dug-cum-bore and bore wells are also common.

It has been observed that in most of the cases necessary geohydrological investigations for the site selection of percolation tanks have not been made. However, it is necessary to go in for detailed hydrogeological investigations in order to ensure the effectiveness of the percolation tanks for groundwater recharging. Since there is limited information available about the rate of recharge and area of influence under these tanks, attempts are required for systematic investigations in this direction. The question whether groundwater should be managed on a sustained or mining yield basis is not yet fully resolved and is controlled more by local conditions, and demand than by policy decisions in advance of their absolute necessity.

Artificial recharge is one of the means to meet the water requirement during drought period. However, artificial recharge means cannot be resorted to without identifying i) the source of water for recharging,ii) suitable method of recharging, iii) spatial and temporal distribution of recharged water, and iv) ground water quality.

4.3 Weather Modification

Weather modification through cloud seeding has been the subject of much research during the past four decades for drought mitigation. There have been conflicting reports on the efficacy of the measure. The reliability of predicting water supply increased from weather modification is still inconclusive.

Some experiments in Florida,USA in dynamic cloud seeding indicated that the benefit-cost ratio waa as high as 31:1 and rainfall of about one lakh acres was attributed to the seeding. Experience in Japan, indicates a 20% increase in precipitation in a 5 years ground based experiment. USSR considers rain making as a proven success. Israel's experience indicates an overall increase of 18%. In India, experiments in cloud seeding have been conducted since 1960 at Jaipur for 4 monsoon periods (1960-63), at Agra for 6 monsoon periods, and at Delhi for 9 monsoon periods (1957-61,1963-66). Clouds were seeded for two summer seasons over the Munar hills in south India. An increase of 20% in precipitation may perhaps be attributed to ground based cloud seeding. Though, the Indian experience in cloud seeding is quite long, yet it is difficult to say without doubt or controversey whether these experiments point to a definite success.

5.0 CONCLUSION

5.1 General Discussion

Reliable estimation of drought is necessary for the overall planning and management of water resources. An exhaustive review of the literature on droughts indicated a large gap in our understanding of the phenomenon and its analysis (i.e. definition, quantification, incidence, severity, duration,trends, forecasting and prediction). Most of the earlier definitions of drought have been defined using rainfall data alone. Later, the set of indices were developed using various parameters. Most of the drought indices now in use have only an empirical value and reflect the adhoc nature of studies in pursuit. There is, not yet an example of the use of integrated, interdisciplinary sets of drought indices, either theoretically designed of practically applied and tested. The time dimension is a crucial aspect in these indices. It could be as short as weeks for agriculture and as long as years for groundwater storage etc.

The Palmer index which takes account of detailed hydrological accountings has been mostly used. Monthly Palmer indices computed for Indian conditions (George et.al.,1973) does not appear to describe realistically the drought conditions in most of the semi and dry sub- humid regions of the country. It has been further modified by Balme & Mooley

(1979) by introducing a modified weighting factor and severity equation. But it is still to be thoroughly tested. The weekly Palmer indices using observed or computed evapotranspiration (by Penman/mofidied Penman method) may prove to be more fruitful.

Water balance approach has been used by most of the workers in drought studies. It seems to be better approach for assessing water deficits and surplus for basins and correlating to droughts. Since drought is a direct consequence of water shortage which can be determined by a comparative study of the marches of precipitation and potential evapotranspiration with due recogniition of the catelytic role of the soil, improved water-balance approach finds place in evolution of drought studies. The correct estimation of evapotranspiration under conditions of soil drying poses difficult problems in water-balance studies.

Even, the most practical water-balance 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 the water balance procedures can be effected to obtain realistic estimates. While defining the droughts, plant physiological aspects should also be considered (particularly the critical growth states).

Theory of runs has been most widely used for analysis of hydrological droughts using streamflow data. In such studies, the deficit of water below a reference value (i.e. truncation level) is analysed in terms of the duration(run-length) and magnitude(run-sum). The detailed statistical procedures in ' analysing the characteristics of run-length and run-time are yet to be fully developed. Stochastic modelling of low stream flows during the drought periods has been done for predicted the droughts. These models essentially aims at preserving the statistical characteristics. Physically based stochastic models like Tank model etc. may be tried for semi-arid and or dry-sub-humid river basins and tested to verify its utility in predicting low flows during droughts. The probabilistic forecasting of drought on the basis of probability distribution of estimates of soil-water deficits of a catchment using the improved water-balance model could also be a suitable approach for short term forecasting of drought.

Although, the preceding, drought concepts differ in many ways, they all require the analyst to consider a certain set of decisions to accurately define the drought event. The set of events consists of following :

i) Selection of the nature of water deficit i.e. hydrological (streamflow etc), meteorological (precipitation),or agricultural (soil-moisture) ;

ii) Selection of averaging period to discretize a continuous time series (months, seasons, or years) depending upon the purpose of study ;

iii) Selection of truncation level used to separate droughts from remainder of time series (mean or meadian); and

iv) Method of regionalization or standaridzation. The type of regionalisation depends upon the particular method of frequency analysis used.

There are number of short and long term drought control measures/strategies. It is felt that planning and execution of works like crop production, water harvesting, agro-forestry pasture development etc. on 'watershed'basis may prove to be more effective in moderating the drought affects in rainfed/ dry land agriculture areas of the country. Percolation tanks have been found to be quite effective in drought prone areas of the country for artificial recharging of groundwater. In addition to this certain drought relief measures like food for work etc. are also required.

5.2 State-of-knowledge on Droughts

On the basis of the review made, the state-of-knowledge on droughts can be summed up as below:-

1. There is no general agreement on definitions and methods of describing the drought phenomena.

2. It is basically understood to be moisture deficiency situation in a region in relation to agriculture and/or human needs. Therefore, the term has different connotations for different climatic, terrain and land use conditions, with the variable technological inputs available.

3. Long range forecasting of droughts can be considered as unpredictable with the present state-of-art on the

subject.

4. Feasibility of probabilistic analysis of hydrological aspects has been demonstrated for drought estimation.

5. Evaluation of drought impacts on morphology of the streams, water levels in various water bodies and water quality is not well attended.

6. The number of practices are available for integrated land and water resources management but the implementation of the known-technology needs to be geared up. Watershed is recommended to be a unit of planning and managing these resources.

7. The construction of water harvesting structures and percolation tanks is being recommended. But the correct assessment of recharge to ground water due to these structures seems to be unattended in a more rigorous manner.

5.3 Future Research Needs

1. A drought situation should be analysed and assessed not only with respect to the meteorological parameters, but should also involve terrian factors like water availability, soil conditions, plant structure and drought resistance, competitive water demands etc.,

2. A comprehensive evaluation of existing drought indices (i.e. their logical representativeness and statistical reliability), and the subsequent improvement and

development of new indices may be taken up.

3. Assessments are needed to test various improved soil moisture storage models for different soils by considering water content profiles. Availability of moisture has direct relation to estimating droughts, particularly agricultural and hydrological droughts.

4. The another problem being faced is the correct assessment of actual evapotranspiration rates for vaiying degree of soil moisture stress and crop parameters for different agro-climatic regions.

   Therefore, evaluation of specific evapotranspiration models, creation of net work of stations for regular determination of evapotranspiration by Lysimeters and for monitoring soil moisture regime under different land use conditions would prove to be of immense help in studying the drought phenomenon.

   Thus, the understanding of physical processes in the soil phase of water cycle would permit better hydrologic interpretation of regional soil moisture as in index of expected trends.

5. The probabilistic analysis of hydrological aspects like precipitation, soil moisture, stream flow, ground water depletion in the aquifers, may,however, be used to estimate the risk of water deficit and attendant drought to plan drought mitigation strategies.

6. Spatial and temporal distribution of recharged water in

the area of interest for the given means of artificial recharging i.e. Percolation tanks etc. may be worked out. The water quality aspects of recharged groundwater may also be studied.

7. The use of Landsat imagery(repetitive) as a tool in monitoring the terrain during dry season and droughts to study changes in soil moisture conditions, vegetal cover, surface water bodies etc. and short term forecasting of droughts from this data may be explored.

8. Effect of soil and water conservation measures on watershed basis for drought mitigation may be studied.

9. System approach and mathematical modelling to evaluate the various strategies for drought mitigation to arrive at the optimum strategey should be adopted.

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APPENDIX I

PALMER INDEX

Palmer index model is an elaborate and comprehensive technique for computing the severity of droughts on the basis of current and antecedent rainfall, evapotranspiration and soil moisture. It requires a month-by-month water balance accounting for a long record, such as 30 years or more. Palmer used two-layer soil model and the Thornthwaite method of computing potential evapotranspiration. However, the methdology does not require any particular method of computing P E. The steps involved in evaluating the Palmer index are briefly described below :

i) CAFEC precipitation: Instead of long term mean values, Palmer used CAFEC values (i.e. Climatically Appropriate For (Existing Conditions), indicated by circumplex. Rainfall anomaly is used as the crucial parameter in Palmer's technique. The CAFEC precipitation is an imaginary amount of precipitation that will maintain at normal level all the established human activities of a place. Thus the, CAFEC precipitation in the period concerned required to maintain 'normal' evapotranspiration, runoff and soil moisture considering the antecedent moisture condition is given by

$$\hat{P} = \hat{ET} + \hat{R} + \hat{Ro} - \hat{L} \quad \ldots(1)$$

where,

P = CAFEC precipitation

$\hat{ET}$ = CAFEC evapotranspiration = αPE ;

$\hat{R}$ = CAFEC soil moisture recharge = β PR ;

$\hat{Ro}$ = CAFEC runoff = γ PRO ;

$\hat{L}$ = CAFEC soil moisture loss =δ PL.

α β γ and δ are the coefficients of evapotranspiration soil moisture recharge, runoff and soil moisture loss respectively.

Coefficient of evapotranspiration(α) : Ratio of the computed mean monthly evapotranspiration(ET) to mean monthly potential evapotranspiration (PE)

$$\alpha = \frac{\overline{ET}}{\overline{\quad}}$$

This ratio is near 1.0 in humid climates, but approaches zero in very arid regions.

Ceofficient of recharge(β) : Ratio of mean monthly moisture gain i.e. recharge (R) to mean potential recharge (PR).

$$\beta = \frac{\overline{R}}{\overline{PR}}$$

Coefficient of runoff (γ): Ratio of computed mean runoff (Ro) to mean potential runoff.

$$\gamma = \frac{\overline{Ro}}{\overline{PRo}}$$

Coefficient of loss (δ) : Ratio of mean moisture loss (L) to mean potential loss (PL)

$$\delta = \frac{\overline{L}}{\overline{PL}}$$

where bar denotes long term mean value.

ii) Hydrologic accounting: Palmer considered that the effective soil depth is made up of two layers viz., a surface layer with 25 mm of available moisture at field capacity and an underlying layer. When precipitation is more than potential evapotranspiration, actual evapotranspiration (ET) equals potential value (PE). Excess of precipitation over PE then goes to recharge the surface layer and after it reaches field capacity it goes to recharge the underlying layer. Runoff takes place only after both the soil layers reach field capacity. When precipitation is less than potential evapotranspiration, actual evapotranspiration(ET) is equal to precipitation plus moisture lost from the soil layers. Loss of moisture from surface layer is assumed to take place at potential rate.

The moisture loss from surface underlying layer is given by

$$Ls = S's \text{ or } (PE-p) \text{ which-ever is smaller, and}$$

$$Lu = (PE-P-LS)\,\frac{S'u}{AWC}\;,\; Lu \leq S'u$$

where, Ls and Lu are moisture loss from surface and underlying layers respectively. S's and S'u are available moisture (actual values) in surface and underlying layer respectively at the start of the month, and AWC is the combined available water capacity of both layers.

Using the above assumptions and relations, values of ET, R,Ro and L are computed. Potential values of these parameters are computed as below:

Potential recharge(PR) : Amount of moisture needed to bring the soil (both layers) to field capacity:

$$PR = AWC - S'$$

where, S' is the total available moisture in both the layers at the start of month (i.e. S's + S'u)

Potential loss (PL) : Amount of moisture that could be lost from the soil if no precipitation occurred in the month.

$$PL = PLs + PLu,$$

where, PLs = PE or S's whichever is less, and

$$PLu = (PE-PLS) \frac{S'u}{AWC}$$

Potential runoff(PRO) : Total amount of moisture storage available.

$$PRO = AWC - PR = S'$$

Palmer used this relation, but indicated that PRO could be defined as $3\bar{P} - PR$ (WMO,1975a).

iii) Rainfall anomaly :

From the computed monthly CAFEC precipitation, the rainfall anomaly (d) is worked out viz.,d = p-p. Anomaly thus obtained being not comparable in time and space, multiplication of the same is suggested by an empirical weighing factor(k) which depends upon average moisture supply (P+L) average moisture demand (PE + R + Ro) and the long term mean of the absolute values of the precipitation anomaly $(P - \hat{P})$ of the region. This factor K tends to be high in arid regions and small in humid regions. The anomaly index, $Z = kd$, provides a measure which is comparable in space and time.

The monthly weighting factor is given by (WMO, 1975 a)

$$K = 448.8 \; K'/DK' \qquad \ldots(2)$$

where,

$$\bar{D} = |P - \hat{P}| \text{ , absolute moisture departure}$$

$$K' = 1.5 \log_{10} \left[\left(\frac{\overline{PE} + \bar{R} + \overline{Ro}}{\bar{P} + \bar{L}} + 2.80 \right) \frac{25.4}{\bar{D}} \right] + 0.50$$

when values are expressed in mm ...(3)

iv) Drought index equation

Inas much as a succession of months, most of which were abnormally dry, produces a drought of gradually increasing severity, the final drought index (x) depends on the sequence of Z (Z = kd) values. These were combined by the empirical equation.

$$x_i = x_{i-1} + \frac{Z_i}{3.0} - 0.103 \quad x_{i-1}$$

$$= 0.897 \; x_{i-1} + \frac{Z_i}{3}$$

where,

x_i is the value of the index for the current month and x_{i-1} for the previous month, z_i, weighted rainfall anomaly of the current month.

The values of x would range from greater than + 4.0 (very humid conditions) to less than -4.0 (extreme drought condition). Palmer gave the following criteria for describing the intensity of drought.

Index value	Intensity class of drought
- 1.00 to -1.99	Mild drought
- 2.00 to -2.99	Moderate drought
- 3.00 to -3.99	Severe drought
-4.00	Extreme drought

v) Determination of commencement and termination of droughts

Near normal conditions are taken to prevail when the index value is between -0.5 and + 0.5. The anomaly Z_e required to end the drought of any month i can be found out from the equation(2) by putting $X_i = -0.5$, so $Z_e = -2.691 X_{i-1} - 1.5$

Similarly, there is a certain minimum value of anomaly which can occur month after month and still maintain the index value at near normal category (+ 0.5 to -0.5) and with no change in the value of index i.e. $X_i - X_{i-1} = 0$. Thus equation

$$X_i = X_{i-1} + \frac{Z}{3} - .103\, X_{i-1} \quad \text{becomes}$$

$$0 = \frac{Z}{3} - .103\,(-0.5)$$

$$Z = -0.15$$

The amount of dryness effective in ending a wet period, therefore, will be the anomaly of the month minus 0.15.

Drought index computations are commenced when after a wet spell, the anomaly Z of a month becomes + 0.15 for the first time. Effective dryness of the month is Z -0.15 and Z_e value required to end in one month the wet spell prevailing at the start of the month is $-2.691 X_{i-1} + 1.5$. The ratio

$\frac{Z\ 1\ 0.15}{-2.691 \times X_{i-1}}$ + 1.5 x 100 gives the percentage probability of ending of the wet spell. If the wet spell has not ended in this month as seen from the probability percentage being less than 100%, then the probability percentage is calculated for successive months by a process of integration till probability becomes either 100% (wet spell has ended) or 0% (wet spell has not ended). If the wet spell has ended, then from the first month of testing drought has commenced and its index value from that month towards gives the appropriate drought index. Once the index value becomes -1.0 or less, drought is established and the index value is calculated using the relation $X_i = 0.897\ X_{i-1} + \frac{Z_i}{3}$ till Z_i becomes greater than -0.15 when Z_i becomes greater than =0.15, testing for the commencement of wet spell is done in a similar manner. Drought is taken to end in the month previous to the one in which the wet spell commences.

APPENDIX II

Climatic-Crop-Growth-Index

The climatic-crop-growth index (CCGI) incorporates the crop tolerance to water stress besides the variations in climatic factors. Expression of rainfall amounts representing various crop growth limits are as follows:

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

The authors have calculated annual and monthly CCGI values and emphasize that monthly values would be more useful in planning the control measures.