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Application of Water Balance concepts for a Climatic Study of Droughts in South India

V. P. SUBRAHMANYAM and A. R. SUBRAMANIAM

Department of Meteorology and Oceanography, Andhra University, Waltair

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ABSTRACT. Droughts in India are widely known to be caused by failures of monsoon—the main source of rainfall. These droughts are usually at the root of many famines and, therefore, they constitute an important study in applied climatology.

As droughts are not mere shortages of rainfall, they can never be defined without reference to moisture available in the soil; they are today regarded to be such periods of dryness that affect the growth and development of vegetation.

Of the several methods of drought study, the water balance method which compares the water supply of a region by precipitation with water need or potential evapo-transpiration has gained wide usage due to its versatility and has been successfully used by Palmer in the United States of America. Hence, this method was employed for the analytical study of droughts in this paper.

Initially, a standard map of climatic types of India prepared by Subrahmanyam according to the 1955 scheme of Thornthwaite was taken and three representative stations—Bijapur (Arid), Trichy (Semi-arid) and Cuddalore (Dry sub-humid)—were selected from the dry climatic zones of south India. Yearly aridity indices for each station were evaluated for a period of 65 years (1891—1955) and their time-trends along with the 7-year overlapping means were graphed and presented. Drought years were picked from these diagrams and their water balances discussed in relation to the climatic situations normal to the stations.

1. Introduction

It is usually very difficult to discover generalizations which are applicable to the whole of India stretching, as it does, from the 8th to the 38th degrees of north geographical latitude and possessing almost every type of climate found in other parts of the world. But perhaps the most striking and, in this connection at any rate, the most important of its features is that a considerable proportion of its population is occupied in an industry—the agriculture—the success of which is almost wholly dependent on a sufficient and well-distributed rainfall through the growing season.

Since practically the entire rainfall over a major portion of the country is derived from the monsoons, the failure or delay in the onset of the latter affects the agricultural production and hits hard on national economy. Such rainfall failures, commonly known as 'droughts', are at the root of many famines and, therefore, they constitute an important study in applied climatology. Droughts are a physical phenomenon producing serious biological effects mainly due to the moisture imbalance in the complex relations between the plant and its habitat. Deserts, thus, are extreme cases of aridity resulting from the permanent prevalence of droughty conditions. Between such absolute deserts at one end practically devoid of plant life and super-humid regions flourishing with luxuriant rain-forests at the other, there exist several other intermediate climates supporting vegetation species of a highly varied character. While the agricultural potentialities of these various zones are determined by the nature of the general climate, the successful crop culture in a given climate depends on the vagaries of water balance, or to use the climatologist's language, the intensity and duration of the droughts. The present work was undertaken with this purpose in view and in the first instance an attempt has been made to apply the well-known water balance concepts of Thornthwaite to a few selected stations in the dry climatic areas of south India and examine the individual drought situations in relation to normal climatic conditions.

2. Definitions of Drought

A very popular and widely accepted definition of drought is "dryness due to lack of rain". Tannehill (1947) states that droughts belong to that class of phenomena known as "spells of weather". In regions with adequate rainfall, the word 'drought' may be applied to a period with low or no rain. Quite often droughts are discussed in terms of deviations of actual rainfall from the normal. Hoyt, for example, says that in the humid and semi-arid climates droughts do not result until the annual precipitation is as low as 85 per cent of the mean. The British Rainfall Organization (Met. Off., London 1936) has defined an 'absolute drought' as a period of at least 15 consecutive days to none of which is credited a rainfall of 0·1" or more. According to Russell, the word drought in Australia is used to signify "a period of months or years during which little rain falls and the country gets burnt up, grass and water disappear, crops become worthless and sheep and cattle die". In the recent 'Glossary of Meteorology' (Amer. met. Soc. 1959) drought has been defined as "a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance (*i.e.*, crop damage, water supply shortage etc) in the affected area". It is further stated therein that "the term should be reserved for periods of moisture deficiency that are relatively extensive in both space and time".

In order, therefore, to understand the drought problem in India, it is necessary to appreciate the conditions of agricultural practice—the crops here are numerous and vary both in kind and season according to the fertility of the soil and general meteorological conditions. Not only does every deficiency mean disaster for the cultivation, but the mere prolongation of the pre-monsoon dry season by a week or fortnight may render vain all hopes of a normal harvest for that year. Ground-water levels sink so low that rivers and other natural water storages dry up and wells cease to be of use. Although droughts producing severe economic strain are frequent in parts of India, they are fortunately not spread all over the country every year: historical records show no example of a serious drought affecting the whole of India. However, one cannot define drought as shortage of rainfall alone since this does not take into account the important part played by soil moisture on which plants depend for their existence. Landsberg (1958) thus states that drought is not a physical but a biological phenomenon and should, therefore, be defined separately for each plant species and soil environment. Shantz (1927) wrote earlier that "drought begins when plants can no longer recoup water from the soil as quickly as it is lost by transpiration". The mere cessation of rain is, therefore, no indication of the beginning of drought; accordingly, Thornthwaite (1947) considered drought as "a period of dryness, *i.e.*, want of rain or water, especially such dryness of weather or climate as affects the earth and prevents the growth of plants". Drought conditions may thus be said to prevail whenever precipitation is not sufficient to meet the needs of established human and other biological activities.

3. Past work

Work so far on droughts may be divided into three groups based on (*a*) Statistical techniques using rainfall data alone, (*b*) Non-statistical methods and (*c*) Water budget methods.

(*a*) *Statistical techniques*

Walker (1912) classified rainfall deficiencies in India as 'large', 'serious' and 'disastrous' according as the year's deficiency lay respectively between 30 and 45 per cent, between 45 and 60 per cent and over 60 per cent of the normal. In view of the popular speculation that the Madras State had undergone a change in rainfall regime during the period 1947-1951, Rao (1958) undertook an analytical study of all the monthly or annual rainfall records of the Madras State. He showed that this was not unique and that a similar period of low rainfall was experienced in the first half of the 19th century from 1828-1835. Majumdar (1958) also made a study of droughts by the application of the statistical theory of runs for determining the recurrence interval of a succession of droughts. Williams (1958) studied the frequency of droughts in South India and showed that the State of Mysore was affected to the least extent by the vagaries of weather. His analysis which was based on annual rainfall figures only did not reveal even a single year of severe drought in any of the states of South India during 1901-1950. Pant (1958) studied the annual rainfall trends of three east coast stations—Masulipatam, Kakinada and Visakhapatnam—for over 90 years using the methods of moving averages, cumulative deviations and least squares; he could not, however, draw any definite conclusions due to inhomogeneity of the available rainfall data. Banerji (1952) discussed the weather factors in the creation and maintenance of the Rajasthan desert, by analysing the rainfall data of a few selected stations. His conclusion was that as all the areas showed negative departures and the statistical probability of such a thing happening on accidental coincidence is very small, the increasing aridity of the Rajasthan must be real. But Rao's detailed examination of the rainfall data (Rao 1958) revealed that there was no significant change in the rainfall normals of the Rajasthan as a whole during the fifty-year period 1901-1950. The apparent differences in certain districts were ascribed by him to differences in the number of stations that entered into the computation of normals and not due to variations in rainfall incidence.

Jameson (1932) in his study of droughts at Colombo, classified them as southwest monsoon and northeast monsoon droughts. Among the several papers on drought studies based on rainfall alone, and supported by effects on agriculture, livestock and streamflows, special mention must be made of the work of Foley (1957) in Australia. The problem was investigated by him primarily from the view-point of deficiency of rainfall compared with the average for all years of record. Periods of rainfall deficiency were illustrated by means of cumulative totals of departures from the averages of monthly rainfall through all the years of record. From the spot-diagrams of duration *versus* amount of deficiency, Foley determined the degree of severity (high, moderate or low) of any particular drought, relative to experience in the concerned area. His drought severity index was, however, based entirely on rainfall deficiency and did not take into account the amount of moisture in the ground at the beginning of the drought period or other factors as temperature, evaporation, wind etc. His procedure may, therefore, be of use in such places where the progressive accumulation of water deficiency (even of small magnitudes) eventually produces drought situations lasting for several months or years. On the general method of cumulative residuals Barnard (1956) states that the technique should be used with extreme care, for otherwise some immediately apparent changes in a time-series may turn out to be not real ones.

Ramdas (1950) in India reviewed 75 years of rainfall record in quest of liability of different zones to floods and droughts. The terms 'flood' and 'drought' were with reference to variation of rainfall only: drought was denoted as an occasion when the actual rainfall fell short of the normal by more than twice the mean deviation and flood as an occasion when actual rainfall exceeded the normal by more than twice the mean deviation. On this basis he prepared a chart of floods and droughts from 1875 to 1949 for various sub-divisions in India. Ramdas also made a separate week-by-week study of rainfall in which flood was considered as a situation when the actual rainfall of the week was twice the normal or more, while a drought was deemed to have occurred when the actual rainfall of the week fell to half or less of the normal.

(b) Non-statistical methods

Knochenhauer (1937) in Germany used the daily maximum temperature and the value of atmospheric humidity at the afternoon observation for the purpose of defining dry spells; this is based on his finding that a dry spell was usually initiated by a sudden rapid increase of from 3° to 4° C in the maximum temperature. According to Gaussen (1954), drought exists whenever the total monthly precipitation in millimetres is less than twice the mean centigrade temperature. On a standard graph with months as abscissa and temperature and precipitation as ordinates, curves are drawn with suitable displacement for water held in the soil. A condition of drought is considered to exist when the temperature curve reaches a height superior to the curve of precipitation. Gaussen was concerned in this study with only the duration but not intensity of the droughts.

(c) *Water–budget methods*

Although statistical techniques are quantitative in character, they often lack the physical back-ground while the non-statistical ones are purely empirical. The water-budget methods, on the other hand, are not only quantitative but are also based on rational concepts. Palmer (1956) defined a drought index using a general book-keeping procedure for determining water deficits. He compared the actual difference between observed monthly rainfall and computed evapo-transpiration with the median value for the particular month, using a soil storage of 6″ of available water. This index, plotted against time, indicates the severity of droughts and also helps the comparison of several drought-periods.

Perhaps the only worker so far that reported a general study of aridity in India according to the water-balance approach was Subrahmanyam (1958). His study was, however, of climatic importance and broadly outlined the application of water-balance procedure evolved by Thornthwaite (1948) in the delineation and analysis of droughts. The present work stems from the above paper and deals with the climatology of droughts in peninsular India.

4. Water Balance and Droughts

Thornthwaite (1947), in his paper on "Climate and Moisture Conservation", identified three different kinds of droughts: permanent droughts of the driest climates, seasonal droughts prevalent in regions with marked wet and dry seasons and finally what he calls "the contingent droughts" which result from the fact that rainfall is irregular and variable everywhere. Thus while the permanent droughts are characteristic of deserts, the contingent droughts are a feature of the humid climates alone. The seasonal droughts, on the other hand, are found in the intermediate climatic zones namely, the semi-arid and the sub-humid. Of these the sub-humid are the border-line climates always susceptible to severe and sudden fluctuations in water balance and, therefore, deserve special study. The semi-arid climates originate due not only to insufficiency but also strong seasonality of rainfall. The techniques for drought analysis should, therefore, be evolved depending on the purpose for which the study is subsequently used. In a country like India with its pronounced monsoonal regime of rainfall the problems of water are two-fold: excessive precipitation in the short rainy season when there is not much need for water, followed by practically no rainfall for a long period when water shortage is very acute. In a rational study of droughts and their impact on national economy it is necessary, therefore, to delineate the major climatic types before proceeding to analyse such arid situations. Thus, in the present work, a standard map of climatic types of India formerly prepared by Subrahmanyam (1956) according to the 1955 scheme of Thornthwaite (Thornthwaite and Mather 1955) was taken and from this map areas belonging to the dry climates, namely, arid (E, I_m less than —40), semi-arid (D, I_m between —40 and —20) and dry sub-humid (C_1, I_m between —20 and 0) could be clearly identified. The average annual water balances of several stations belonging to each zone were then graphically examined in order to choose those representing the above three major dry

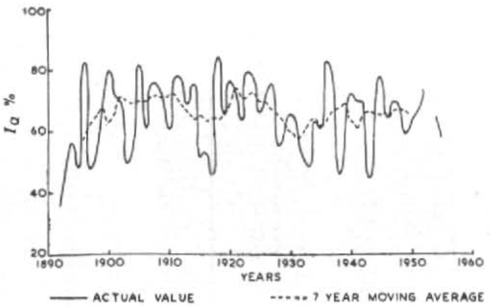

Fig. 1. Bijapur

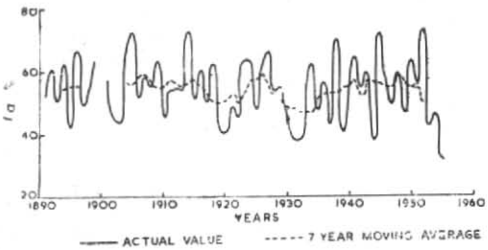

Fig. 2: Trichy

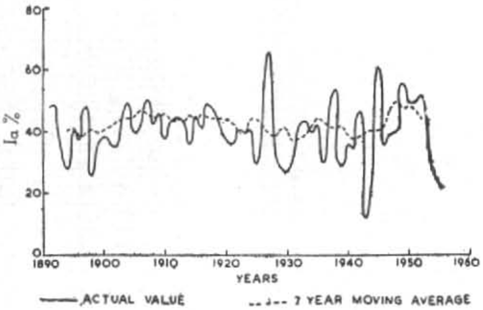

Fig. 3. Cuddalore

climatic types, from similarities in the seasonal curves of water need and rainfall. Fifteen stations were finally selected from different sections of India falling under these dry climates. In the present study three stations from peninsular India have been used; Bijapur (75° 43′ E, 16° 49′ N, I_m =—40) from the arid, Trichy (78° 42′ E, 10°49′N, I_m =—31·7) from the semi-arid and Cuddalore (79° 46′ E, 11°46′ N, I_m =—7·1) from the dry sub-humid zones, and their data of rainfall and temperature subjected to climatological analysis from the water balance angle.

5. Present work

For the analytical study of droughts on an annual basis, the aridity index of Thornthwaite (I_a, which is the ratio of annual water deficiency to the total annual water need, expressed as a percentage) has been considered to be a useful parameter. The moisture index, I_m, may be of use on such climatic situations where water deficiencies and surpluses alternate in quick succession so that the intensity of dryness in periods of drought is mitigated on account of the soil moisture accumulated during rainy periods. Where, however, there is a short rainy season followed by a prolonged dry season, as is the case in most sections of India, the moisture stored in the soil in the wet period is almost entirely used up soon after the setting-in of the dry season; as a result, a long period of pronounced dryness invariably precedes every rainy season. In such circumstances, the use of the aridity index rather than the moisture index is found to be more appropriate.

Following the book-keeping procedure of Thornthwaite (1948) the yearly water balances of Bijapur for 64 years (1892-1955), of Trichy for 64 years (1891-1899 and 1901-1955) and Cuddalore for 65 years (1891-1955) were worked out and the aridity indices evaluated for each year. The time-trends of their actual values as well as their 7-year over-lapping means are shown graphically plotted in Figs. 1 to 3 which reveal certain common features—the rapid fluctuations of the absolute index values superposed on a gradual variation of the moving means. It should naturally be expected that in the years in which the peaks of the absolute curve coincide with rises of the moving average, the water deficit would be most severely experienced causing droughty

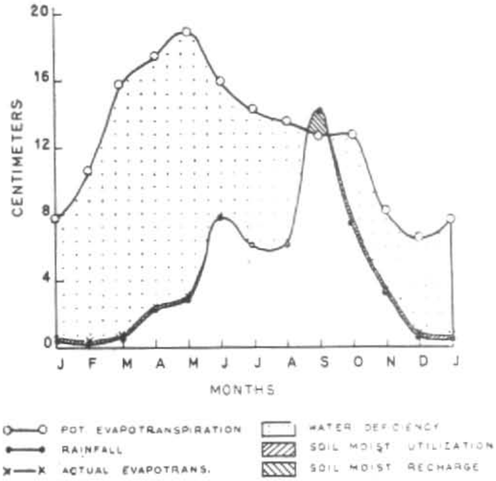

Fig. 4(a). Bijapur—Climatic

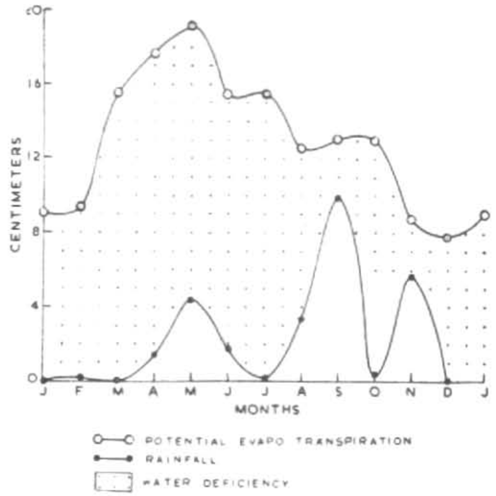

Fig. 4(b). Bijapur—1936

TABLE 1

Station	Years
Bijapur	1905, 1923 and **1936**
Trichy	1914, **1927** and 1945
Cuddalore	1907, 1927, 1938 and **1949**

conditions. It has, however, not been possible to assign critical values to the aridity index that determine the onset or persistence of droughts owing to the non-availability of evidences from agricultural and other statistics. Nevertheless, in each case, years have been picked for which the I_a was about the maximum for the rising portion of the average trend and the water balances for such years were studied in detail month by month. Table 1 shows the years so obtained for the three selected stations in peninsular India.

Since water deficiency represents the amount by which precipitation fails to meet the demands of evapo-transpiration after all the soil moisture has been used up, it is an approximate measure of supplemental irrigation required for the efficient growth and development of vegetation. Thus, a study of water balances in severe drought years would appear to be essential in order to provide an idea of the acute water shortages experienced in such extreme situations. Table 2 shows the water balances of the three stations for the three severe drought years indicated in bold types in Table 1.

Table 3 gives the climatic water balances of the above stations.

For purposes of comparison, in Table 4 are presented the annual moisture data of the stations for normal and the selected drought years.

Figs. 4 to 6 are graphical representations of the water balances given in Tables 2 and 3. Bijapur, situated in the arid zone, has its rainfall always below the water need (Fig. 4 a) except in September when there is a slight rainfall excess (1·4 cm) which is temporarily stored in the soil and used in a restricted way for evapo-transpiration during the subsequent months. This means that there is more actual evapo-transpiration in the rainy season due not only to increased precipitation but also to transpiration from the desert vegetation that springs into foliage at this time of the year. In 1936 (Fig. 4 b) Bijapur had its rainfall not matching the water need even in September and so

TABLE 2

Water balances according to the 1955 scheme of Thornthwaite

(All values are in cm)

	J	F	M	A	M	J	J	A	S	O	N	D	Year
							BIJAPUR (1936)						
P.E.	9·0	9·3	15·5	17·6	19·1	15·4	15·5	12·5	13·1	13·0	8·8	7·8	156·6
P.	0	0·2	0	1·4	4·4	1·8	0·1	3·4	9·8	0·3	5·6	0	27·0
A.E.	0	0·2	0	1·4	4·4	1·8	0·1	3·4	9·8	0·3	5·6	0	27·0
W.D.	9·0	9·1	15·5	16·2	14·7	13·6	15·4	9·1	3·3	12·7	3·2	7·8	129·6
W.S.	0	0	0	0	0	0	0	0	0	0	0	0	0
							TRICHY (1927)						
P.E.	14·4	14·0	16·7	17·8	18·8	17·8	17·7	17·6	16·1	15·7	13·3	11·9	191·8
P.	0·4	0·4	0·7	2·1	2·0	7·3	4·2	3·2	18·8	10·2	10·2	4·3	63·8
A.E.	1·0	0·8	0·9	2·3	2·1	7·3	4·2	3·2	16·1	10·6	10·5	4·7	63·8
W.D.	13·4	13·2	15·8	15·5	16·7	10·5	13·5	14·3	0	5·1	2·8	7·2	128·0
W.S.	0	0	0	0	0	0	0	0	0	0	0	0	0
							CUDDALORE (1949)						
P.E.	8·5	8·9	14·0	16·7	18·0	17·7	17·2	16·8	16·1	15·6	11·2	8·7	169·4
P.	0	0	0	0·4	10·6	10·6	19·5	10·2	7·1	5·2	10·8	0·8	75·2
A.E.	0·2	0·2	0·1	0·5	10·7	10·6	17·2	10·6	7·6	5·7	10·8	1·0	75·2
W.D.	8·3	8·7	13·9	16·2	7·3	7·1	0	6·2	8·5	9·9	0·4	7·7	94·2
W.S.	0	0	0	0	0	0	0	0	0	0	0	0	0

TABLE 3

Climatic water balances according to the 1955 scheme of Thornthwaite

(All values are in cm)

	J	F	M	A	M	J	J	A	S	O	N	D	Year
							BIJAPUR						
P.E.	7·7	10·6	15·7	17·4	18·9	15·9	14·2	13·5	12·7	12·7	8·1	6·5	153·9
P.	0·5	0·2	0·5	2·2	2·8	7·7	6·0	6·1	14·1	7·3	3·2	0·6	51·2
A.E.	0·6	0·4	0·6	2·4	2·9	7·7	6·0	6·2	12·7	7·5	3·4	0·8	51·2
W.D.	7·1	10·2	15·1	15·0	16·0	8·2	8·2	7·3	0	5·2	4·7	5·7	102·7
W.S.	0	0	0	0	0	0	0	0	0	0	0	0	0
							TRICHY						
P.E.	10·5	12·7	15·4	17·8	19·0	18·2	18·3	17·6	16·4	15·3	13·2	10·3	184·7
P.	2·5	1·2	0·9	4·6	8·4	4·1	3·4	9·7	12·0	18·3	14·8	7·1	87·0
A.E.	3·6	2·2	1·8	5·1	8·7	4·3	3·6	9·7	12·0	15·3	13·2	7·5	87·0
W.D.	6·9	10·5	13·6	12·7	10·3	13·9	14·7	7·9	4·4	0	0	2·8	97·7
W.S.	0	0	0	0	0	0	0	0	0	0	0	0	0
							CUDDALORE						
P.E.	9·3	10·9	12·3	16·8	18·9	16·9	18·2	17·1	15·8	14·7	12·0	10·0	172·9
P.	6·1	2·3	1·8	2·5	2·5	3·6	6·6	12·2	13·2	29·2	39·4	19·0	138·4
A.E.	9·2	9·0	7·8	7·9	6·3	5·4	7·6	12·5	13·4	14·7	12·0	10·0	115·8
W.D.	0·1	1·9	4·5	8·9	12·6	11·5	10·6	4·6	2·4	0	0	0	57·1
W.S.	0	0	0	0	0	0	0	0	0	0	13·6	9·0	22·6

P.E.=Potential Evapo-transpiration, P=Precipitation, A.E.=Actual Evapo-transpiration, W.D.=Water Deficiency and W.S.=Water Surplus

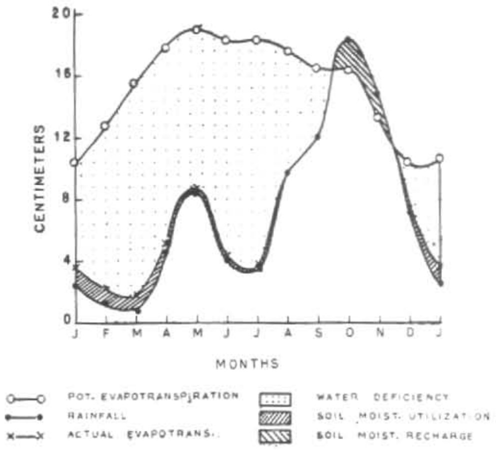

Fig. 5(a). Trichy—Climatic

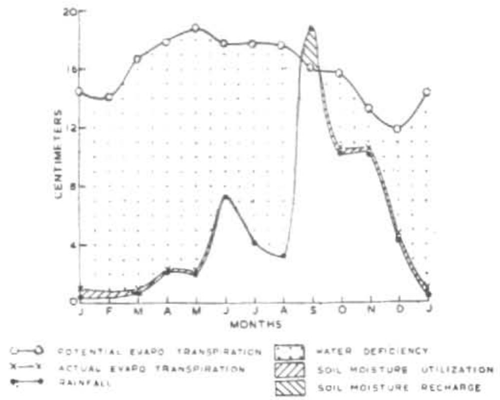

Fig. 5(b). Trichy—1927

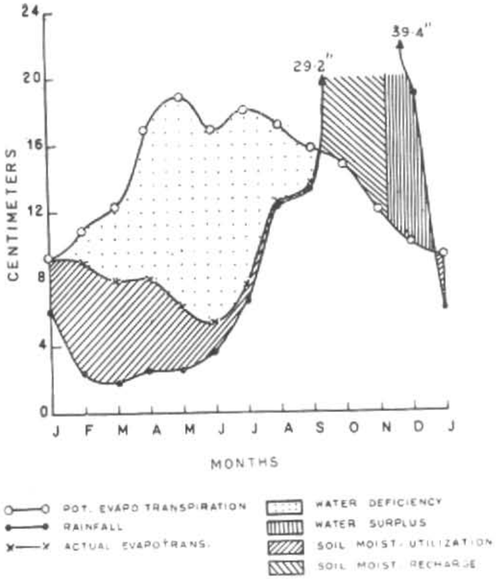

Fig. 6 (a). Cuddalore—Climatic

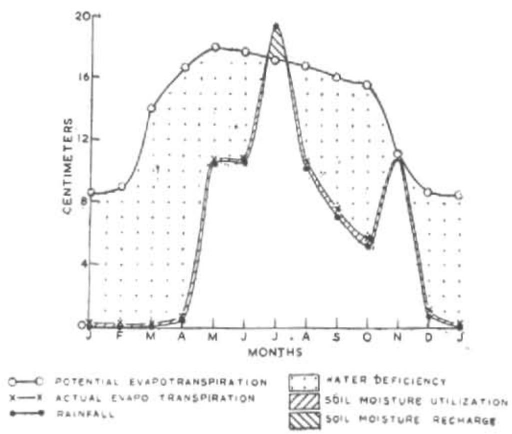

Fig. 6(b). Cuddalore—1949

there was water deficiency throughout the year. This diagram is more typical of the absolutely arid conditions that prevail here though in certain exceptionally wet years, the monthly precipitation may exceed the demands of P.E., throwing the climate even into the sub-humid category.

On the other hand, at Trichy which comes under the semi-arid climate there is almost every year (Fig. 5 a) a short rainy season in which enough or slightly more precipitation is received temporarily recharging the soil reservoir; the excess (4·6 cm), however, is hardly sufficient to raise the soil to saturation and produce runoff. During the drought year 1927 (Fig. 5 b) this surplus was only 2·7 cm which was not adequate even for the next month's water demand. Thus, in this year, Trichy experienced a water deficiency of 128·0 cm, about 30 per cent more than the climatological average of 97·7 cm.

Cuddalore has a dry sub-humid climate possessing highly variable water balances. Climatically (Fig. 6 a) it has an annual water surplus of 22·6 cm accumulated essentially during the months of November and December while the rainfall excess in October and early part of November is entirely used for the replenishment of soil moisture. This soil moisture reserve is almost completely drained by April for purposes of evapotranspiration and from May until August, large water deficiencies accumulate. Even so, in these sub-humid climates, no year can be usually taken as representative of the moisture regime, for here the water balance year after year oscillates violently between surplus and deficit situations. The year 1949 (Fig. 6 b) is, therefore, not typical of the sub-humid conditions prevailing at Cuddalore but has been presented to illustrate the critical nature of water balance in an established drought year. As a matter of fact, in extremely dry years the moisture balance here may resemble that of an arid climate (compare with Bijapur—climatic) while in a wet year it may be superior to

TABLE 4

Comparative moisture data in cm

	P.E.	P	A.E.	W.D.	W.S.
Bijapur (1936)	156·6	27·0	27·0	129·6	0·0
Climatic	153·9	51·2	51·2	102·7	0·0
Trichy (1927)	191·8	63·8	63·8	128·0	0·0
Climatic	184·7	87·0	87·0	97·7	0·0
Cuddalore (1949)	169·4	75·2	75·2	94·2	0·0
Climatic	172·9	138·4	115·8	57·1	22·6

P.E.=Potential Evapo-transpiration

P=Precipitation

A.E.=Actual Evapo-transpiration

W.D.=Water Deficiency

W.S.=Water Surplus

that of a humid station. It is precisely for these reasons that the sub-humid climates (moist or dry) are considered to possess critical water balances and it is here that serious efforts are needed not only for combating droughts as they occur but also to conserve the meagre water resources in times of rainfall excess for use in subsequent dry periods.

The work reported in this paper is admittedly preliminary but the approach can be seen to be of promise for a rational study of droughts and aridity. Applied on a monthly or seasonal basis, it may yield useful information to the agriculturist in his irrigation scheduling and to the hydrologist in his project operations.

6. Acknowledgement

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