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Drought recurrence in different climatic regions in India

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Abstract

The droughts are recurring natural phenomenon, governed by regional climatic parameters. The mean annual precipitation and mean annual potential evapotranspiration are the readily available climatic parameters. The ratio of mean annual precipitation (P_a) to global terrestrial mean annual precipitation (P_g), and ratio of mean annual potential evapotranspiration (E_p) to mean annual precipitation (P_a) have been used to define the climatic regions. This is an attempt to develop relationship between average drought frequency and evapotranspiration/precipitation ratio in arid, semi-arid and sub-humid climatic regions in India. The average drought frequency (i e., yr^{-1}) is found to decrease gradually from dry to wet regions. The return period varies from two to three years in the arid regions ($12> E_p/P_a \geq 5$), three to five years in semi-arid regions ($5>E_p/P_a \geq 2$), and five to eight years in sub-humid regions ($2>E_p/P_a \geq 3/4$). Also, another relationship describing the average frequency of occurrence in terms of the ratio of mean annual deficit to mean annual precipitation, $(E_p-P_a)/P_a$ is developed. The results have been compared with the documented drought experiences elsewhere. These relationships may contribute as a reliable tool for the prediction of regional drought frequency and a base for further critical analysis of drought and for planning of drought management strategies for a given region.

INTRODUCTION

Droughts are regional in nature, i.e., they are driven by regional meteorological conditions. Therefore, their occurrence is related to regional climatic parameters (Dracup, et al., 1980a; Ponce et al., 2000). The common climatic parameters referred to are the mean annual precipitation and mean annual potential evapotranspiration. The mean annual precipitation at a given place depends on several factors, among them are: (1) latitude, (2) season, (3) orographic factors, (4) proximity to oceans, (5) mesoscale atmospheric circulation, (6) atmospheric pressure, and (7) character of the Earth's surface. Another common climatic parameter is mean annual potential evapotranspiration, which depends on: (1) net solar radiation, (2) vapor pressure deficit, (3) surface roughness, and (4) leaf area index (Monteith, 1965). Drought frequency (F) refers to the number of years that it would take a drought of a certain intensity to recur, in units of yr; for instance, once in 10 yr. The reciprocal of the frequency is the return period or recurrence interval. In common usage, however, frequency and return period are often used interchangeably, for instance, a frequency of 10 yr.

A drought year is one with less than average precipitation. A drought event is a series of one or more consecutive drought years. Drought duration, intensity, and frequency are known to vary across the climatic spectrum (Gregory, 1989; Dracup et al. 1980a; Ponce et al., 2000). A meteorological drought can have a duration of one or more years. Since dry periods are generally followed by corresponding wet periods, it follows that recurrence interval of drought is always greater than drought duration. Since the time unit considered in this study is a year, therefore, minimum duration of a meteorological drought is one year and the minimum drought return period can be two years.

While there is an extensive global literature on droughts, but its systematic documentation is lacking. In the current hydrologic literature, devising a suitable universal definition of drought has proven to be an abstruse task (Yevjevich 1967; Dracup et al., 1980b). A number of researcher have used precipitation as the principal indicator in drought analysis (Bogardi et al. 1994; Mohan and Rangacharya, 1991; Herbst et al., 1966; Sharma, 1997b). Dracup et al. (1980a) recommended that if one is interested in determining causes or characteristics of drought, the attention should be focussed on the meteorological (precipitation) droughts. However, if one is interested in determining the effect or impact of drought, attention should be focussed on streamflow and agricultural drought. The commonly used time unit for drought analysis is the year followed by season and month (Sen, 1980; Dracup et al. 1980a; Dracup and Kendal, 1988). Annual precipitation records can be successfully used to define droughts (Dracup et al. 1980b and Bonacci, 1993).

This study attempts to relate average drought frequency with evapotranspiration-precipitation ratio in the arid, semiarid and sub-humid climatic regions in India. The basic assumption in this paper is that the main cause of drought is a precipitation deficit in an area compared with the average precipitation in that same area in an analysed period of time. All other characteristics are more or less directly influenced by the precipitation deficit in space and time. The climatic regions are defined in terms of mean annual precipitation, or alternatively, in terms of mean annual potential evapotranspiration (Ponce et al., 2000). It is believed that a relationship characterizing regional drought frequency in terms of either of these two parameters provides an appropriate framework for the systematic analysis of droughts.

DROUGHT PRONE AREAS AND THE DATA ANALYZED

In terms of geographical area and population, drought prone area accounts for nearly One-Third of total area of the country and 29% of the population (Sikka, 1986; Central Water Commission, 1982). Drought prone areas fall in three broad regions of the country. The plateau region embodies states of Andhra Pradesh, Karnataka, Maharastra, Madhya Pradesh, Orissa, Tamil Nadu, Bihar, West Bengal and Uttar Pradesh; second, desert region encompasses the states of Rajasthan and Gujrat; and third, few districts in the states of Haryana and Jammu & Kashmir also encompass drought prone areas (Central Water Commission, 1982).

The data used in this study included 95 rainguage stations located in drought prone areas in India, which include variety of rainfall records (for 65 to 89 years) from arid to sub-humid climatic regions. The location of the selected stations is shown in Fig.1. The details of the data used are given in Table 1. The year for which rainfall data is not available, have not been accounted in the analysis. To estimate potential evapotranspiration rates, 30 years daily meteorological data from various stations were used. The evapotranspiration were estimated using Penman (1963) method and compared with the data published by India Meteorological Department (IMD) in Sci. Report No. 136 (Rao, et al. 1971).

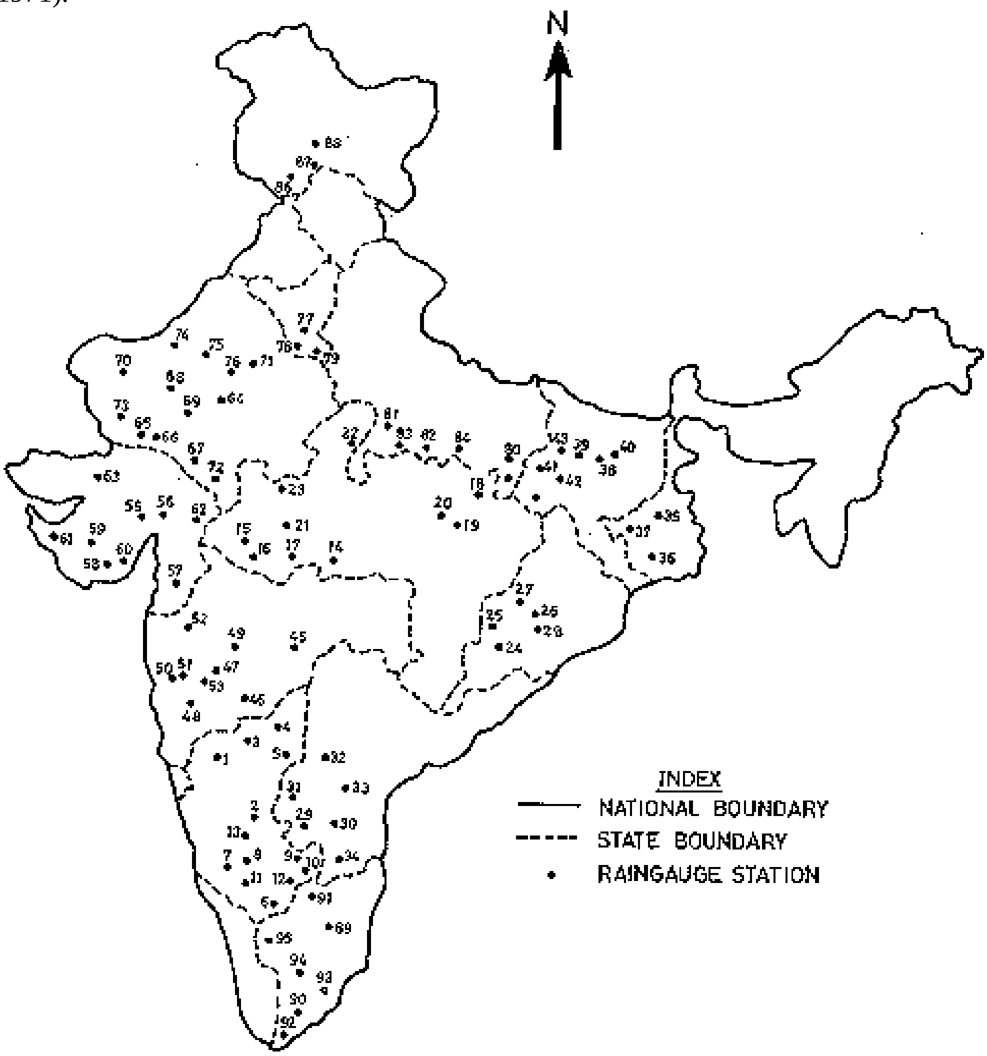


Figure 1. Location of selected stations in different climatic regions in India.

Table 1. Details of selected locations and data analyzed for drought characterization in different climatic regions in India.

Sl. No	Name of place	Location	Length of rainfall records	Years of missing data	E_p/P_a Ratio
	(1)	(2)	(3)	(4)	(5)
1.	Belgaum, Karnataka	15° 49'N 74° 51'E	88 yrs 1901-88	--	1.097
2.	Bellary, Karnataka	15° 09'N 76° 51'E	87 yrs 1901-87	--	3.373

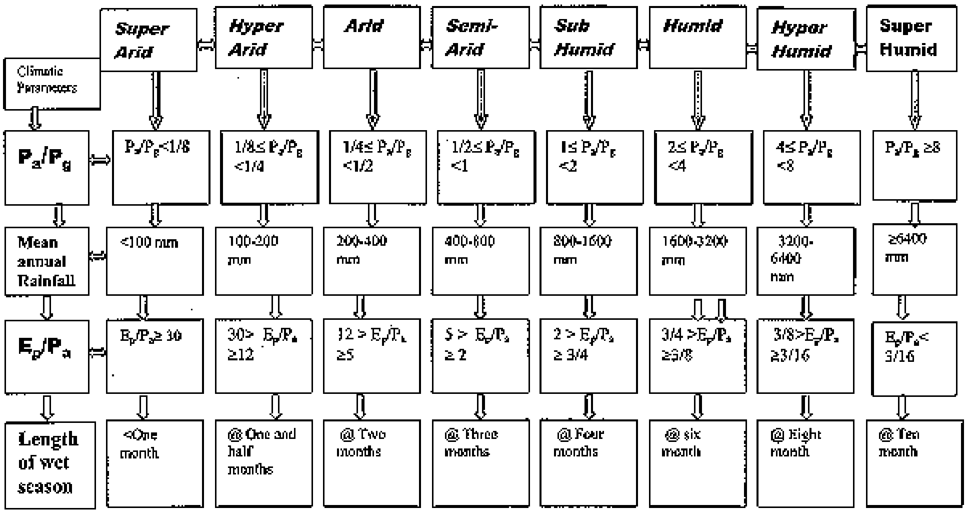
3.	Bijapur, Karnataka	16° 49'N 75° 43'E	87 yrs 1901-87	--	2.846
4.	Gulbarga Karnataka	17° 21'N 76° 51'E	81yrs 1901-86	1945-47, 49, 72	2.441
5.	Raichur Karnataka	16° 12'N 77° 21'E	85 yrs 1902-86	--	2.933
6.	Mysore Karnataka	12° 18'N 76° 42'E	80 yrs 1901-80	--	1.972
7.	Chikmanglure Karnataka	13° 20'N 75° 46'E	79 yrs 1901-80	1949	1.521
8.	Tumkur Karnataka	13° 21'N 77° 06'E	79 yrs 1901-80	1965	1.836
9.	Kolar Karnataka	13° 00'N 78° 08'E	80 yrs 1901-80	--	2.156
10	BangaloreNorth Karnataka	12° 75'N 77° 34'E	80Yrs. 1901-80	--	1.665
11	Hassan Karnataka	13° 00'N 76° 15'E	76 Yrs 1901-80	1945,65, 67, 68	1.623
12	Mandya Karnataka	12° 32'N 76° 53'E	79 Yrs 1901-80	1904	2.004
13	Chitradurg Karnataka	14° 17'N 76° 25'E	80 yrs 1901-80	--	2.519
14.	Betul Madhya Pradesh	21° 55'N 77° 54'E	87 yrs 1901-87	--	1.365
15.	Dhar Madhya Pradesh	22° 33'N 75° 18'E	83 yrs 1901-89	1951-56	1.972
16.	Jhuabua Madhya Pradesh	22° 47'N 74° 35'E	77 yrs 1901-87	1951-56, 62-64, 73	1.836
17.	Khargoan Madhya Pradesh	21° 49'N 75° 31'E	53 yrs 1931-89	1951-56	2.149
18.	Sidhi Madhya Pradesh	24° 24'N 81° 53'E	87 yrs 1901-89	1916, 21	1.162
19.	Shahdol Madhya Pradesh	23° 25'N 81° 26'E	80 yrs 1901-80	--	1.206
20.	Umaria Madhya Pradesh	23° 35'N 80° 54'E	89 yrs. 1901-89	--	1.130
21.	Dewas Madhya Pradesh	22° 40'N 86° 23'E	68 yrs. 1913-80	--	1.693
22.	Datia Madhya Pradesh	25° 40'N 78° 28'E	67 yrs. 1905-77	1936, 37, 38, 48, 49, 50	1.887
23.	Shajapur Madhya Pradesh	23° 27'N 76° 16'E	67yrs. 1907-80	1925, 26, 27, 28, 63, 66, 67	1.599
24.	Bhavanipatna, Kalahandi, Orissa	19° 55'N 83° 10'E	84 yrs. 1901-96	1949-60	1.112
25.	Nawapara Orissa	20° 17'N 82° 46'E	67 yrs. 1918-96	1948-55, 86, 90-92,	1.242
26.	Phulwani Orissa	20° 29'N 84° 14'E	84 yrs. 1901-96	1949-60	1.040
27.	Bolangir Orissa	20° 22'N 83° 29'E	36 yrs. 1961-96	--	1.434
28.	Boudh Orissa	20° 50'N 84° 19'E	80 yrs. 1903-96	1949-61, 77	1.264
29.	Anantpur Andhra Pradesh	14°41'N 77° 37'E	76 yrs. 1910-85	--	3.316
30.	Cuddappa Andhra Pradesh	14°29'N 78° 50'E	85 yrs. 1901-85	--	2.422
31.	Kurnool Andhra Pradesh	15° 50'N 78° 04'E	85 yrs. 1901-85	--	2.884
32	Mahboobnagar Andhra Pradesh	16° 44'N 77° 59'E	85 yrs. 1901-85	--	2.025
33	Prakasam Andhra Pradesh	15° 34'N 80° 03'E	85 yrs. 1901-85	--	1.992
34	Chittoor Andhra Pradesh	13° 13'N 79° 09'E	85 yrs. 1901-85	--	1.905
35	Bankura, West Bengal.	23° 14'N 87° 04' E	60 yrs. 1901-78	1943, 46, 47, 50-52, 55-65, 77	1.078
36	Midnapur, West Bengal.	22° 25'N 87° 19' E	81 yrs. 1901-81	--	0.960
37	Purulia, West Bengal.	23° 20'N 86° 23' E	75 yrs. 1902-80	1911, 15, 23, 48	1.070
38.	Nawada Bihar	24° 53'N 85° 33' E	77 yrs. 1901-80	1971-73	1.608
39	Gaya, Bihar	24° 45'N 84° 57' E	70 yrs.1901-74	1970-73	1.469
40	Munger, Bihar	25° 23'N 86° 40' E	75 yrs. 1901-80	1961-64, 67	1.169
41	Rohtas (Sasaram), Bihar	25° 57'N 84° 02' E	74 yrs. 1901-80	1960, 63, 65, 70-72	1.314
42	Aurangabad, Bihar	24° 45'N 84° 23' E	65 yrs. 1901-70	1963-65, 67, 68	1.400
43	Bhojpur, Bihar	25° 34'N 84° 40' E	68 yrs. 1901-69	1965	1.401
44	Palamu, Bihar	24° 03'N 84° 04' E	79 yrs. 1901-80	1970	1.177
45	Bhir, Maharastra	18° 59'N 75° 46' E	62 yrs. 1901-78	1957, 62-74, 76, 77	2.505
46	Solapur (North), Maharastra	17° 40'N 75° 54' E	69 yrs. 1901-78	1945, 57, 62, 64-67, 71, 76	2.554
47	Ahmednagar, Maharastra	19° 05'N 74° 48' E	78 yrs. 1901-78	--	2.642
48	Satara, Maharastra	17° 41'N 73° 59' E	73 yrs. 1901-77	1966-69	1.559
49	Aurangabad, Maharastra	19° 53'N 75° 47' E	77 yrs. 1902-79	1976	2.431
50	Hulsi, Pune, Maharastra	18° 32'N 73° 37' E	77 yrs. 1901-77	--	0.929
51	Pune, Maharastra	18° 32'N 73° 51' E	75 Yrs. 1901-75	--	2.186

52	Osmanabad, Maharastra	18° 10'N 76° 02' E	74 Yrs. 1901-78	1963-66	2.158
53	Nasik, Maharastra	20° 00'N 73° 47' E	65 Yrs. 1901-76	1951, 63-70, 73,74	2.542
54	Ahmedabad, Gujrat	23° 09'N 72° 38' E	80 Yrs. 1901-80	--	2.142
55	Mahmedabad, Kheda, Gujrat	22° 50'N 72° 45' E	79 Yrs. 1901-80	1960	2.040
56	Rajkot, Gujrat	22° 18'N 70° 50' E	78 Yrs. 1901-80	1953, 55	3.468
57	Bharuch, Gujrat	21° 41'N 72° 59' E	80 Yrs. 1901-80	--	2.024
58	Jafrabad, Amreli, Gujrat	21° 36'N 71° 13' E	76 Yrs. 1901-80	1961, 62, 70, 73	3.581
59	Surendranagar, Gujrat	22° 59'N 71° 28' E	80 Yrs. 1901-80	--	4.036
60	Bhavnagar, Gujrat	21° 45'N 72° 12' E	78 Yrs. 1901-80	1971, 72	2.958
61	Jamnagar, Gujrat	22° 29'N 70° 04' E	68 Yrs. 1901-80	1915, 16, 51-60	3.432
62	Kalol, Panchmahal, Gujrat	22° 37'N 73° 38' E	79 Yrs. 1901-80	1962	1.721
63	Bhuj, Kuchchh, Gujrat	23° 15'N 69° 48' E	79 Yrs. 1901-80	1960	5.392
64	Nagaur, Rajasthan	27° 12'N 72° 45' E	87 Yrs. 1901-88	1978	5.132
65	Jalor, Rajasthan	25° 21'N 72° 37' E	88 Yrs. 1901-88	--	3.988
66	Bhinmal, Jalor, Rajasthan	25° 01'N 71° 46' E	86 Yrs. 1901-88	1951, 59	3.545
67	Udaipur, Rajasthan	24° 35'N 71° 42' E	87 Yrs. 1902-88	--	2.152
68	Jodhpur, Rajasthan	26° 18'N 73° 01' E	88 Yrs.1901-88	--	5.032
69	Pali, Rajasthan	25° 47'N 73° 20' E	87 Yrs. 1901-88	1971	3.851
70	Jaiselmer, Rajasthan	25° 55'N 70° 55' E	85 Yrs. 1901-88	1960, 64, 71	10.875
71	Jhunjhunu, Rajasthan	28° 08'N 75° 23' E	85 Yrs. 1901-88	1977-79	3.738
72	Dungarpur, Rajasthan	28° 51'N 73° 43' E	87 yrs 1901-88	1978	2.151
73	Barmer, Rajasthan	25° 45'N 71° 24' E	88 yrs. 1901-88	--	6.893
74	Bikaner, Rajasthan	28° 00'N 73° 18' E	88 yrs 1901-80	--	6.088
75	Churu, Rajasthan	28° 18'N 74° 58' E	82 yrs 1906-88	1964	6.825
76	Ajmer, Rajasthan	26° 27'N 74° 37' E	87yrs 1901-88	1972	3.324
77	Rohtak, Haryana	28° 54'N 76° 35' E	74Yrs. 1901-78	1966, 69, 70, 74	3.055
78	Rewari,Mahrndragarh, Haryana	28° 12'N 79° 33' E	75Yrs. 1901-80	1966, 69, 70, 71, 74	2.528
79	Gurgaon, Haryana	28° 28'N 77° 02' E	75Yrs. 1901-80	1964, 71, 74, 77, 78	3.659
80	Varanasi, Uttar Pradesh	25° 18'N 83° 01' E	69 Yrs. 1901-73	1961-64	1.470
81	Jalaun, Uttar Pradesh	26° 08'N 79° 20' E	69 Yrs. 1901-73	1961-64	1.991
82	Banda, Uttar Pradesh	25° 29'N 80° 21' E	71 Yrs. 1901-73	1957, 58	1.862
83	Hamirpur, Uttar Pradesh	25° 37'N 80° 08' E	69 Yrs. 1901-73	1961-64	1.825
84	Chail, Allahabad, Uttar Pradesh	25° 28'N 81° 50' E	80 Yrs. 1901-80	--	1.605
85	Mirzapur, Uttar Pradesh	25° 09'N 82° 35' E	73 Yrs. 1901-73	--	1.536
86	Kishtwar, Jammu & Kashmir	33° 18'N 75° 45' E	64 Yrs. 1901-81	1950, 52-61, 63-68	1.033
87	Bhadarwah, Jammu & Kashmir	32° 59'N 75° 43' E	59 Yrs.1912-81	1950-59, 68	0.939
88	Udhampur, Jammu & Kashmir	32° 52'N 75° 02' E	68 Yrs. 1901-68	--	0.568
89	Salem, Tamilnadu	11° 39'N 78° 10' E	78 Yrs. 1901-78	--	1.795
90	Tiruneveli, Tamilnadu	08° 47'N 77° 41' E	76 Yrs. 1901-76	--	1.956
91	Dharmapura, Tamilnadu	12° 08'N 78° 10' E	80 Yrs. 1901-80	--	2.025
92	Kanyakumari, Tamilnadu	08° 10'N 77° 27' E	76 Yrs. 1901-77	1970	1.715
93	Ramnathpuram, Tamilnadu	09° 23'N 78° 35' E	74 Yrs. 1901-74	--	2.196
94	Madurai, Tamilnadu	10° 21'N 77° 58' E	77 Yrs. 1901-77	--	1.034
95	Coimbatore, Tamilnadu	11° 0' N 76° 58' E	80 Yrs. 1901-80	--	3.273

P_a=Mean annual precipitation (mm) and E_p= Mean annual potential evapotranspiration (mm)

CLIMATIC CLASSIFICATION

The climatic regions can be defined in terms of two readily identified parameters: (1) mean annual precipitation, and (2) mean annual potential evapotranspiration. This type of characterization is particularly useful for midlatitudinal regions, where droughts are shown to be more intense (Karl, 1983). Ponce et al. (2000) have classified the climatic spectrum in midlatitudinal regions using the ratio of local mean annual precipitation (P_a) to global terrestrial mean annual precipitation (P_g) and the ratio of mean annual potential evapotranspiration (E_p) to mean annual precipitation (P_a). The global terrestrial mean annual precipitation (P_g) subjects to interpretation. The average moisture in the atmosphere depends on latitude and climate, varying typically in terrestrial regions in the range 2 - 50 mm (2 -15 mm for polar and arid regions, to 45-50 mm for humid regions) with a mean global terrestrial value of 25 mm (Unesco, 1978). This moisture recycles every eleven days on the average, for a total of 33 annual cycles (L'vovich, 1979), which results in the global terrestrial mean annual precipitation of P_g = 825 mm. For comparison, L'vovich's (1979) has estimated a value of 910 mm for exorheic drainages (78.4 percent of total terrestrial area), and 238 mm for endorheic drainages (21.6 percent). This amounts to a weighted value P_g = 765 mm. Ponce et al. (2000) have estimated that at the middle of the climatic spectrum the global terrestrial mean annual precipitation amounts to 800 mm. Assuming a value of P_g = 800 mm, the middle of the climatic spectrum is taken as $P_a/P_g = 1$. Thus, regions with $P_a/P_g < 1$ have less than average moisture. Conversely, regions with $P_a/P_g > 1$ have more than average moisture. Terrestrial mean annual precipitation varies typically in the range 100-6000 mm (Baumgartner and Reichel, 1975). Based on P_a/P_g ratio, the climatic spectrum was divided into the eight regions from super-arid to superhumid as given in Fig 2 (Ponce et al., 2000).



(Source: Ponce et al., 2000)

Figure 2. Flow chart showing climatic classification at a glance.

Potential evapotranspiration of a terrestrial ecosystem is the amount of evapotranspiration that would take place under the assumption of an ample supply of moisture at all times (Thornthwaite et al.,1944). The climatic spectrum can also be characterized by the ratio of mean annual potential evapotranspiration (E_p) to mean annual precipitation (Vysotskii, 1905; Ivanov, 1948; WMO, 1975). Ponce et al., (2000) have defined the suitable limits of E_p/P_a ratios across the climatic spectrum. The arid, semi arid, sub humid and humid climatic regions are defined as $12 > E_p/P_a \geq 5$; $5 > E_p/P_a \geq 2$; $2 > E_p/P_a \geq 3/4$ and $3/4 > E_p/P_a \geq 3/8$ respectively. These limits are indicative of general trends, and not necessarily as exact values separating climatic regions. Also, the above classification closely matches with other existing classifications (Bull, 1991; Dutt, 1986).

In view of the Indian conditions, the classification given by Ponce et al., (2000) is completely justified as the high rates of evapotranspiration prevail over arid Rajasthan, in western India, with annual rates exceeding 2000 mm and reaching 2500 mm in some parts of Northwest Rajastan (Abbi, 1974). Low rates of evapotranspiration prevail over humid Assam and the Himalayan Bengal, in northeastern India, with annual rates in the range of 1000 to 1200 mm. Over the central parts of India, which are semiarid to sub-humid, evapotranspiration rates vary in the range 1400-1800 mm (Abbi, 1974; Rao, 1971). Mean annual precipitation and potential evapotranspiration data from Australia also supports the values chosen for climatic classification (Fig.2). For instance, in hyperarid William Creek, in south Australia, precipitation is 127 mm and potential evapotranspiration is in the order of more than 2540 mm. In arid Alice Springs, in the Northern Territory, precipitation is 250 mm and potential evapotranspiration is 2460 mm. In semiarid/sub-humid Perth, in Western Australia, precipitation is 890 mm and potential evapotranspiration is 1670 mm. In sub-humid Sydney, in New South Wales, precipitation is 1200 mm, and evapotranspiration exceeds 1220 mm (Kendrew, 1961).

ANALYSIS AND RESULTS

The climatic regions are defined in terms of two readily available climatic parameters: (1) ratio of mean annual precipitation to global terrestrial mean annual precipitation (P_a/P_g), and (2) ratio of mean annual potential evapotranspiration to mean annual precipitation (E_p/P_a). The arid, semiarid and sub-humid climatic regions are categorized as the areas with the mean annual rainfall between 200-400 mm, 400-800 mm and 800-1600 mm respectively, and mean annual potential evapotranspiration/precipitation (E_p/P_a) ratio between $5 \leq E_p/P_a < 12$, $2 \leq E_p/P_a < 5$ and $0.75 \leq E_p/P_a < 2.0$ respectively. These climatic regions have an approximate length of wet season as two, three and four months respectively. The mean annual rainfall (P_a) in the selected stations of the country ranges from 259.69 mm at Churu in Rajasthan to 1588.77 mm at Hulsi in Maharastra and the potential evapotranspiration varies from 1372.1 mm at Betul in Madhya Pradesh to 2144.6 mm at Jafrabad in Gujrat .

The most popular perception of a drought is as a ‘meteorological phenomenon’, characterized by lack of rainfall compared to expected amount over a given period of time. Different definitions of drought have been proposed from time to time depending on one’s expectations about moisture needs for specific human activities. For some, a drought exists when rainfall is below 75% of long-term mean (Glantz, 1994), others might consider it to occur at 60 or 50% of normal. In this study a definition suggested by the India Meteorological Department (IMD) is used, i.e., “for a given time period (seasonal/yearly), if a meteorological station/division receives total rainfall less than 75 percent of the normal, it is considered as a drought" (Central Water Commission, 1982).

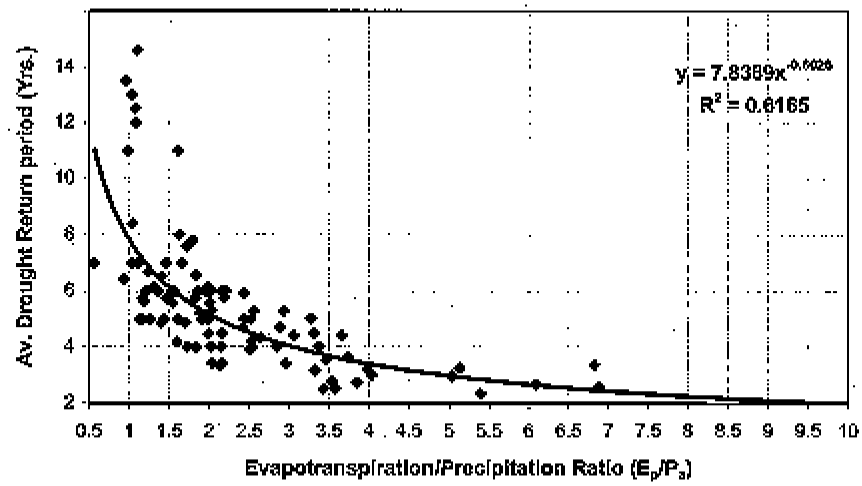


Figure 3. Relationship between ratio of mean annual potential evapotranspiration to mean annual precipitation (E_p-P_a) and average drought frequency.

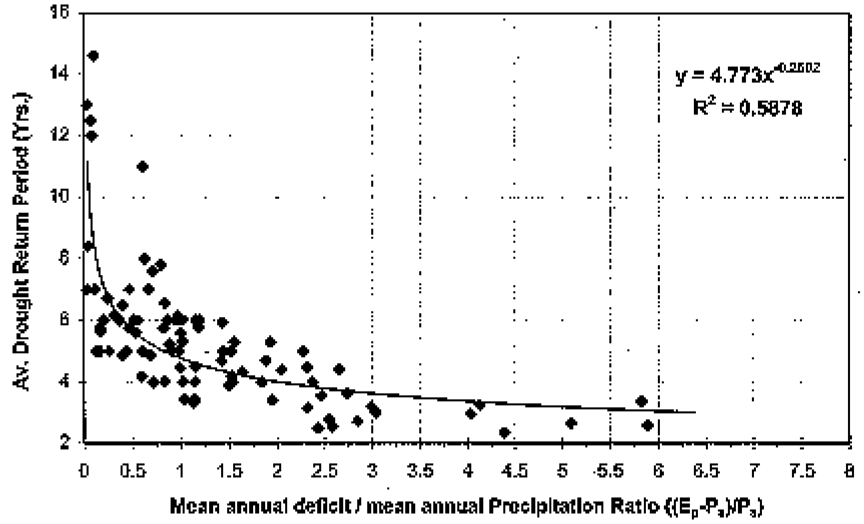


Figure 4. Relationship between ratio of mean annual deficit to mean annual precipitation (E_p-P_a)/P_a) and average drought return period in arid and semi arid regions.

The long-term annual rainfall series (for 65 to 89 yreas) for each station was analyzed using percentage annual rainfall departure to identify the drought years and the drought events. Being a percentage, it is purely qualitative and descriptive in nature. Thus the average drought frequency is obtained as numbers of years of rainfall records analysed divided by numbers of meteorological drought years. Regression has been applied to relate the ratio of mean annual potential evapotranspiration to mean annual precipitation (E_p/P_a) with the average drought frequency (i.e. in terms of return period). The relationship between average drought frequency and E_p/P_a ratio is shown in Fig. 3. The power type regression showed better correlation ($R^2 = 0.652$) as compared to the logarithmic or exponential type regression. Fig.3. shows that the frequency of meteorological droughts has significant relationship with the E_p/P_a ratio. Average drought frequency (expressed in terms of return period i.e. yr) is seen to vary from 2-3 years in the arid regions (with $12 > E_p/P_a \geq 5$), 3-5 years in the semiarid regions (with $5 > E_p/P_a \geq 2$) and 5-9 years in the sub-humid regions (with $2 > E_p/P_a \geq 3/4$). Also, a relationship between the average drought return period and the ratio of mean annual deficit (E_p-P_a) to mean annual precipitation shows similar results (Fig. 4).

Fig.3 reveals that the average drought frequency decreases from arid to sub-humid regions. In the arid and semiarid regions it is decreasing gradually from once in 2.5 yrs. on average to once in 5 yrs. for a long range of E_p/P_a ratio from 2.0 to 10.0 . However, in the wet site (ie. sub-humid regions) it decreases sharply from once in 5 to once in 9 yr for a short range of E_p/P_a ratio from 0.75 to 2.0. Further, a better correlation ($R^2 = 0.6943$) can be seen between the average drought return period and the ratio of mean annual deficit (E_p-P_a) to mean annual precipitation (Fig 5). Thus it can be stated that the drought frequency decreases exponentially with the increase of wetness.

DISCUSSIONS

The relationship between average drought return period and the E_p/P_a ratio (Fig.3) shows a close agreement with documented experiences on drought as discussed below.

For the arid regions with $E_p/P_a \geq 5$, the average drought frequency is found to be once in every 2-3 yrs (Fig.3). This is comparable with the documented drought experience in arid climatic regions in Kazakhstan in Russia, and Sarido in Brazil. In Kazakhstan, which is mostly arid (Zonn et al., 1994), around 35 severe droughts have occurred in the last 100 years, i.e., every 3 yrs on the average (Kogan,1997). The Sarido, which belongs to an arid ecosystem with $E_p/P_a \cong 5.8$ (Ponce 1995a), experiences drought conditions in every 3 years (Magalhaes, 1994). Using long term series of rainfall data, Koteswaram, (1970) reported the periodicity of drought broadly for arid meteorological sub-divisions in West Rajasthan and Saurashtra & Kutch as 2-3 years, which was later suported by the Sastry (1986) and Dutt (1986).

The semi arid areas which receive total annual rainfall in the order of about half of the local mean annual potential evapotranspiration (i e. $E_p/P_a \cong 2$) have experienced drought once in 5 yrs (Fig. 3). In semiarid areas with E_p/P_a ratio between 2.0 to 3.0 and 3.0 to 5.0, the drought recur after every 4-5 and 3-4 yrs respectively (Fig. 3). This is comparable with drought recurrence in Ukraine in Russia, Caatinga and Saritao in Brazil, Georgetown in Australia and, Morocco, Tunisia and Algeria in Northwest Africa. In Ukraine, where climate and soils are favorable for agricultural production (i.e., semi arid) than in Kazakhstan, droughts affect the area after every 4-5 yrs (Kogan, 1997). In semi arid Caatinga and Saritao, where mean annual precipitation ranges between 395 mm to 800 mm and the E_p/P_a ratio varies from 2.2 to 4.8 (Ponce, 1995a), the drought recurs on the order of once in every 5 years (Magalhaes, 1994). French (1987) has analyzed long term series of annual rainfall for Georgetown, in North Central of South Australia, where the mean annual rainfall is 475 mm. The records from 1874 to 1985 show 20 drought events, i.e. an average frequency of once in 5.5 yrs. The Morocco which belongs to a semiarid climatic region (P_a = 400-500 mm) has experienced approximately 25 years of drought during the period from 1901 to 1994 i.e., an average drought frequency of once in 3.5 yrs (Swearingen, 1994). The other Northwest African countries like Tunisia and Algeria also experience roughly the same frequency of drought (Swearingen, 1994). Droughts recur in Gujrat, Eastern Rajasthan and Rayalseema after every 3 years and in South Interior Karnataka, Eastern Uttar Pradesh and Vidarbh the average frequency is once in 4 years (Koteswaram, 1970).

The sub-humid areas, which receive their mean annual rainfall in the order of more or less equal to the local mean annual potential evapotranspiration (i e. $E_p/P_a \cong 1$) experienced less frequent drought. For example, in this study it is observed that the Midnapur, Purulia, and Bankura in West Bengal, Phulwani in Orissa and Belgaum in Karnataka state receive their mean annual rainfall in the order of more or less equal to the local mean annual potential evapotranspiration and have experienced drought with an average frequency of every 14, 8, 13, 12 and 11 years respectively. The average drought frequency in sub humid areas, with E_p/P_a ratio between 1.0 to 2.0, is once in 5 to 7 yrs (Fig. 3). This is comparable with the drought experiences in Agreste and Mata in Brazil and Upper Midwest of the United States. In Agreste and Mata, where the E_p/P_a ratio varies between 1.3 to 2.0 and 0.7 to 1.1 respectively, the drought conditions visit every 8-12 years on the average (Ponce, 1995a and Magalhaes, 1994). For the sub-humid climatic regions in the Upper Midwest of the United States, with mean annual precipitation of about 1500 mm (NOAA, 1980), the average return period of drought is reported as 10 yr, appropriate (Klugman, 1978).

Thus the above comparison of relationship between average drought frequency and regional climatic parameters (E_p/P_a ratio), with drought data and experiences documented throughout the world indicate that the results are reasonably acceptable. These relationships can be used as a base for further critical analysis of drought and for planning of drought management strategies for given areas. The work's strength is its climatic basis, i.e., its ability to depict drought frequency vis-a-vis regional variability of moisture availability.

CONCLUSIONS

The average drought frequency (i.e., expressed in terms of return period yrs.) has been considered as a function of dimensionless climatic parameter derived as (i) the ratio of mean annual potential evapotranspiration to mean annual precipitation (E_p/P_a) and (ii) the ratio of mean annual deficit to mean annual precipitation $\{(E_p-P_a)/P_a\}$. The study revealed that the frequency of meteorological droughts have significant relationship with the E_p/P_a ratio and $(E_p-P_a)/P_a$ ratio. Average drought frequency (F) (i.e. yr^{-1}) is seen to decrease gradually from dry to wet regions, from once in two to three years in the arid regions (12> $E_p/P_a \geq 5$), three to five years in the semiarid regions (5>$E_p/P_a \geq 2$) and five to nine years in the sub-humid regions (2>$E_p/P_a \geq 3/4$). Also, another relationship is obtained between the average drought return period and the ratio of mean annual deficit to mean annual precipitation $\{(E_p-P_a)/P_a\}$. It is hoped that the relationship presented in this paper can be used as a reliable tool for the prediction of regional drought frequency, which is an important parameter in the planning of appropriate drought management strategies for different climatic regions of the country.

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