Drought Monitoring and Management

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INTRODUCTION

Hydrologic extremes refer to the circumstances when there is either too much of water that may cause damages (floods), or too less of water that may cause water scarcity in sustaining usual regional activities and the ecosystem (droughts). Floods and drought have always been a major concern of the society. Despite fascinating achievements of science and technology in 20th century, extreme hydrological events continue to hit human heritage and undermine development by breaking continuity. Devastating droughts and floods can be viewed as enemies of sustainable development (Kundzewicz and Kaczmarek 2000). They cause damage to crops and agricultural farms and induce the threat of famine.

Coping with the droughts has always been a major concern of both developed and developing nations in the world. The rise in water demand has made the society increasingly vulnerable to drought and water deficit. There are a diverse range of drought definitions used by the researchers, but none has got recognition of all. Droughts should not be confused with aridity. Droughts and aridity may be distinguished as follows:

Droughts	Aridity
Drought is generally viewed as regionally extensive occurrence of below average natural water availability, either in the form of precipitation, river runoff or ground water	Aridity applies to the persistently dry regions, where, even in normal circumstances, water is in short supply. In other words, A desert can not be described as a drought area because no one farms or run stocks there and arid nature of the area is accepted

Drought, although hard to believe, can have a greater impact, financially and on human health than flood (Lugo and Morris 1982). Drought affects virtually all climatic regions (Wilhite, 2000) and more than one half of the earth is susceptible to droughts every year (Gol'tsberg 1972). Hewitt (1997) reported that, through out the world, drought ranks first among the natural disasters in number of persons affected.

Inconsistency of variables characterizing the processes of hydrologic cycle is responsible for occurrence of hydrologic extremes. Regions with higher variability of rainfall and runoff are more vulnerable to floods and droughts (Kundzewicz and Kaczmarek 2000). Droughts primarily are perceived due to a significant reduction in precipitation, possibly accompanied by relatively increased temperature and evapotranspiration (Nicholls, 2003). Climate determines kind of crops grown, types of cattle kept and the life style adopted by the people. The ratio of the long-term mean precipitation to potential evapotranspiration determines a climate's classification. Ponce et al. (2000) conducted a study on drought characterization across the climatic spectrum and reported that the middle of the climatic spectrum (i.e. sub-humid, semi-arid and arid climatic regions) has greater inter-annual rainfall variability and is more vulnerable to severe droughts. Also, it is widely believed that the climate change may exacerbate the water stress caused by the population growth and increased demand due to economic development. For example, European simulations show a wide spread increase in drought frequency across much of the Europe

(Impact of climate change, 1997). Similar results were obtained by Whetton et al. (1993) for some regions of Australia. A sensitivity analysis of impact of changes in precipitation and evapotranspiration for three catchments in Poland (Kaczmarek and Napioekowski, 1997) led to the conclusion that increase of rainfall variance has a significant impact on the reliability of water supply.

Drought is generally viewed as regionally extensive occurrence of below average natural water availability, either in the form of precipitation, river runoff or ground water and soil moisture. Notion of drought should not be confused with aridity which applies to the persistently dry regions, where, even in normal circumstances, water is in short supply. In other words, a desert can not be described as a drought area because no one farms or run stocks there and arid nature of the area is accepted. Consequences of droughts are felt most keenly in areas which are in any case arid. However, it is manifested, drought adversely affects the economy by reducing or even eliminating, agricultural production, herds of cattle, energy generation, and domestic and industrial water supply. Out of 328 million ha geological area of India, 107 million ha (nearly one third) is affected by drought. It includes about 39% of cultivable land and about 29 % of our population.

The human society has to get used of the fact that extreme hydrologic events are natural phenomenon that will continue to occur. This paper incorporates elaborative discussions of the present status of understanding about drought in particular. It includes discussions on awareness of definition concepts, assessment techniques, characterization and means of combating drought.

CAUSES AND DEFINITION OF DROUGHT

Almost all of the water vapour in the air comes from the ocean, but not all of it falls back in to the ocean as rain. Instead, the winds move the water-laden air onto the terrestrial land, where it becomes rain. But the system doesn't always work correctly. Sometimes, the winds that are needed to move the water-laden air inland (i.e. onto the interiors of continents), are not strong enough, Or the winds doesn't blow in the right direction at the right time. Thus the moist air doesn't reach onto the regions/continents and the area suffers from drought. In Southeast Asia, the summer winds known as monsoon carry moist air from the Indian Ocean in to far inland. They provide rains that are badly needed after 8-9 months period of dry-winter and dry-summer. Normally, the monsoon winds blow from south to north, but in some years they are blown to one side by winds from west. When that happens, the moist air from Indian Ocean does not reach the Asian subcontinents and this result in poor rainfall and drought. Precipitation deficiencies, due to natural climatic variability in space and time, are therefore the primary cause of droughts.

Various definitions of drought have been proposed from time to time depending on the one's expectations about moisture needs for specific human activities and subject of interest. In the current hydrologic literature, devising a suitable universal definition of drought has become a difficult task (Yevjevich 1967; Dracup et al., 1980b).

Cole (1933) defined drought as a period of atleast 15 consecutive days none of which had rainfall of 2.5 mm or more. According to Hoyt (1936), there is a drought when annual rainfall is less than 85% of normal. Depending on the nature of the water deficit to be studies in terns determines the general drought definition to be adopted. For Example , the U.S. Weather Bureau defines drought as a '*lack of rains so great and long continued as to affect injuriously plant and animal life of a place and to deplete water supplies both for domestic purposes and for operation of power plants, especially in those regions where rainfall is normally sufficient for such purposes'(Havens, 1954).* Ramdas (1960) defined drought as a situation when rainfall is deficient by twice of its mean deviation. Konstantinov (1968) believed that drought should be studied using an analysis of deficit of evapotranspiration, which is defined as the difference between the potential and the real evapotranspiration. Palmer (1965) has defined a drought at a given location, as a period of time, lasting months or years, during which the actual moisture supply consistently falls short of the climatically expected moisture supply. Dracup et al. (1980a) defined drought as a period of time (month/year) with rainfall/runoff below a mean truncation level which is derived from long term rainfall/runoff series. Also, in few countries the droughts are defined in further typical ways. For example, in Libya 'droughts are recognized only after two years without rain' (Hudson and Hazen, 1964) and in Egypt 'any year the Nile does not flood is drought, regardless of rainfall.

However, the most popular perception of a drought is as a 'meteorological phenomenon', characterized by lack of rainfall compared to expected amount for a given period of time. For some, a drought exists when rainfall is below 75% of long-term mean, others might consider it to occur at 60 or 50% of normal (Glantz, 1994). In India, we normally considered a definition suggested by the India Meteorological Department (IMD), 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).

The concept of the definition of drought also varies with the subject of interest. A meteorologist drought refers to a deficiency of precipitation. A hydrologist is concern with unusual lessening of available water in fresh water bodies and soil profile, in an amount sufficient to affect their normal uses. For an agriculturist drought refers to a soil moisture deficiency during cropping period (Karl and Young, 1987; Dracup et al., 1980b). Dracup et al. (1980a) recommended that if one is interested in determining causes (or characteristics) of drought, the attention should be focused on precipitation droughts. However, if one is interested in determining the effect or impact of drought, attention should be focused on stream flow and agricultural drought.

Despite some measure of overlap and major differences in the definition worldwide, following four types of droughts are recognized. These categories have varying features and often need different mitigation strategies.

(i) Meteorological drought: A meteorological drought refers to a deficiency of precipitation, without regard to the application. It is a situation when there is an effective or influential decrease in the amount of precipitation over an area. There is often no direct ecological or economic impact and there is no effective human response.

(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 and rivers, cessation of spring flows and fall in ground water level. This involves the management of water supply and demand aspects.

(iii) Agricultural drought: Agricultural drought refers to a short-term soil moisture deficiency to sustain crops and livestock. It occurs when soil moisture and rainfall are inadequate/ erratic during the growing season to support healthy crop growth to maturity and cause extreme crop water stress and wilt. This involves the on farm water supply and demand including crop-insurance, compensation and loss- sharing measures.

(iv) Socio-economic drought: It is associated with a deficiency of water needed to meet the demand of industrial and urban activities.

Also, in current hydrologic literature, the term "Environmental drought" has been introduced to distinguish/emphasize the adverse consequences of water deficits on ecosystems.

TIME UNITS IN DROUGHT ANALYSIS

After selecting the drought indicator or the nature of water deficit to be studied, the drought analyst must decide which unit of time (or time-step) has to be used for analyzing meteorological or hydrological variables under consideration. Choice of the time-unit is one of the important factors in the analysis of hydrology of extremes. The units of time may vary from 1 hour or less for the analysis of flood events to a decade or more for analyzing large scale climatic changes. For the study of drought events, commonly used time unit is the month followed by season, and year (Sen, 1980; Dracup et al. 1980a; Dracup and Kendal, 1988). For example, drought may be studied as periods of low precipitation lasting an integer number of months, periods of low soil moisture lasting an integer number of growing seasons, or periods of low streamflow lasting an integer number of years. The lower limit of one month is specified because of the distinction made in water resources between low flows and droughts. Low flows usually have durations of the order of daily or weekly flows and for analytical purposes, are considered to occur instantaneously. Low flows are further distinguished from droughts in their sampling procedure. Drought events are drawn from a continuous time series of monthly, seasonal, or yearly data.

The selection of the time-unit for a particular drought study is dependent almost entirely on the purpose for which the study is intended. However, the choice of this time unit affects two aspects of whatever analysis is performed. First, it determines the sample size of events to be studied. For a given length of hydrologic record, a shorter time unit results in a larger number of drought events, however, a longer time-unit results in a smaller number of drought events. For example, the mean annual streamflow for a year may be below the long term normal flow and thereby constitute a drought year, but it is very possible that particular months within that year will experience above normal stream flow and thus separate the single drought year into several month based drought events.

To demonstrate the effect of the length of the time-unit on the sample size of drought events, please see Table 1. It shows the number of streamflow drought of the Ken and Betwa river system in Central India which resulted from the use of monthly, seasonal (three months) and yearly time unit. On the average, the use of annual streamflow data yields about one seventh the drought events of those from monthly streamflow data.

The size of the set of historical drought samples is important in determining the type and accuracy of the analysis that may be performed. The sample size must be large enough to guarantee that the sample statistics (e.g. mean, variance, serial correlation etc) are reasonable approximations of the corresponding population parameters. When the averaging period for

Table 1: Effect of time unit of Sample Size (SS) and Serial Correlation (SC) for streamflow records in Bundelkhand region of Central India.

Stream	Time unit					
	1-month		3- month		1-year	
	SS	SC	SS	SC	SS	SC
Betwa river	56	0.75	12	0.18	9	-0.08
Ken river	68	0.60	16	0.23	7	-0.03
Dhasan river	61	0.58	10	0.05	7	-0.06
Bearma river	57	0.53	14	0.04	6	0.04

droughts events are set at one year, obtaining such an adequate sample size presents a significant problem. For instance, a typical 42 yr. streamflow record in Bundelkhand region contains only 7 multiyear drought events; estimating population parameters from the sample statistics of such a record is risky at best. Therefore, there is a distinct tradeoff between the need to study long period drought events and the need to maintain an adequate sample size which justifies performing accurate analyses on the available data.

The second aspect of drought analysis affected by the selection of an time-unit is the degree of correlation between successive drought events. In general, a shorter averaging period tends to result in greater serial correlation in the time series; thus monthly drought events usually exhibit more serial correlation than yearly ones. The use of longer time periods apparently smoothes out short term affects of natural carryover storage and climatic stability which may have a substantial impact on droughts based on a shorter time-unit. The impact of time unit on serial correlation in hydrologic records for Bundelkhand region is also shown in Table 1. The presence of serial correlation in a time series can cause significant problems in carrying out a frequency analysis since most such methods assume (either explicitly or implicitly) that the data to be studied constitutes a sample of independent events. There is no evidence in the literature that a proven method exists for performing drought frequency analysis, which accounts for non-negligible serial correlation in the data (Dracup et al, 1980a).

Hence, the time-unit that describes a drought event has its affect on the data sample size and the time series serial correlation. A short averaging period (i.e. a month) results in a larger sample size and larger serial correlation; while a long time unit (i.e. 1 year) results in a smaller sample size and smaller serial correlation. Although the selection of the time-unit is often made independently of these considerations (the only criterion being the purpose for which the study is intended), the drought analyst should be aware of the consequences inherent in choosing one time unit or another.

THE TRUNCATION LEVEL

A necessary component of a complete drought definition is a specification of the method by which drought events are abstracted from the remainder of the meteorological or hydrologic time series. This component is termed here as the truncation level, which serves to divide a time series into "above normal" and "below normal" sections. The concept and effect of the truncation level is more clearly seen when the statistical theory of runs is adopted for the analysis of the time series. The runs methodology is useful in analyzing a sequential time series of stochastic or deterministic variables and hence is better suited to the study of hydrologic and meteorological events. The fundamental parameters of the runs of a hydrologic series are shown in Fig. 1. The truncation value X_o can be set arbitrarily to cut the series at several places, and its relationship to all other values of the X series is the basis for defining the other runs parameters. These parameters are the run sum (cumulative deviation from X_o) (S_L) the run intensity (average deviation from X_o), (M_L) and the run length (distance or time between successive crosses of X_o) (D_L). For high flow events these parameters are denoted by S_H, M_H and D_H. Because of the way they are defined, the high-flow and drought events must alternate in sequence (Fig 1). In more common drought terminology, run sum, run intensity, and run length are termed as severity, magnitude, and duration respectively. These three parameters are the fundamental descriptors of drought events. They are related by the following expression (Dracup et al, 1980a).

$$S_L = M_L \cdot D_L \qquad \text{.... (1)}$$

In practice, the selection of X_o is not arbitrary but rather is a function of the type of water deficit being studied. For the study of multiyear hydrologic droughts, X_o may be selected as the mean annual runoff a watershed; for the study of seasonal agricultural droughts, X_o may be selected as the mean soil moisture present during the prime growing season. Theoretically, X_o may be a constant, a stochastic variable, a deterministic function, or any combination of these. For example, to abstract only the most severe droughts from a time series, it may be convenient to choose a function level such as

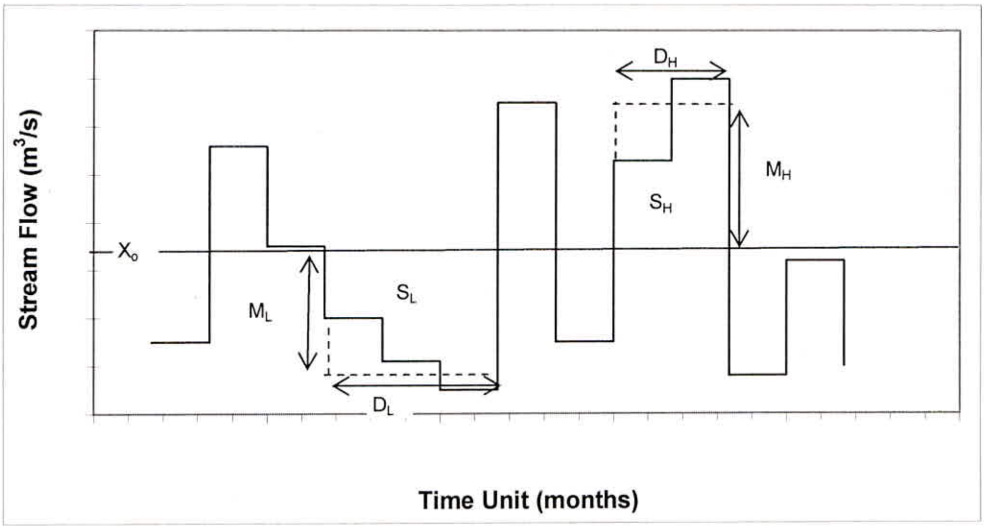


Fig.1 Description of fundamental parameters of runs of a time series

$$X_o = X_m - e.S_d \quad \quad ....(2)$$

Where X_m is the series mean, S_d is the series standard deviation, and e is an elective scaling factor.

In general, the truncation level is chosen to be some measure of the central tendency of the drought sample; this results in approximately half of the events being classified as "high" and half as "low" (Dracup et al. 1980b). Statistics commonly measuring the central tendency of a sample are mean, median, and mode. The median measures the minimum average deviation from the truncation level. The mean, which is more sensitive to the extreme values of the distribution, measures the minimum average deviation squared. Virtually all hydrologic records are skewed, meaning that the mean differs from the median and thus requiring that the analyst choose between the two.

By combining the notion of the truncation level with the notion of the time-unit discussed in the previous section, it is possible to define four categories of hydrologic events, based upon whether they are above or below the truncation level and whether they are of short or long time-unit. These are shown schematically in Fig. 2. The conventional definitions are as follows; "flood" is above X_o with short time-unit, "low flow" is below X_o with short time-unit, "high flow" is above X_o with longer time-unit, and "drought is below X_o with longer time-unit. The lack of symmetry in these conventional definitions is obvious and is an unfortunate aspect of the development of water resource terminology.

It remains then to assess the advantages in using the mean or median as the truncation level to distinguish droughts from the rest of the time series. Utilising a median truncation level yields an identical number of drought and high flow time periods. This occurs if the record length is adjusted so that it contains only complete cycles of drought and high flow events; this new record length can be called the effective record length. If the time series is divided such that the number of drought and high flow periods is the same, then the mean duration of both droughts and high flows must also be the same. This situation would simplify the comparison of duration analysis of these two types of events.

Similarly, using a mean truncation level yields the deviation from X_0 for drought and high flow events when the effective record length is used. As a result both drought and high flows will have the same mean severities. Thus the mean for X_0 would aid in the comparison of drought severity analyses.

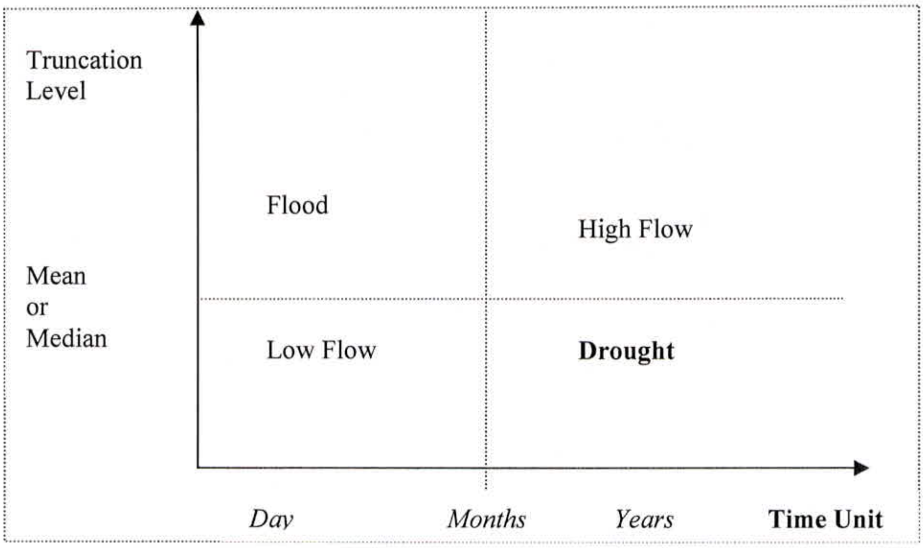


Fig 2: Categorization of hydrologic event

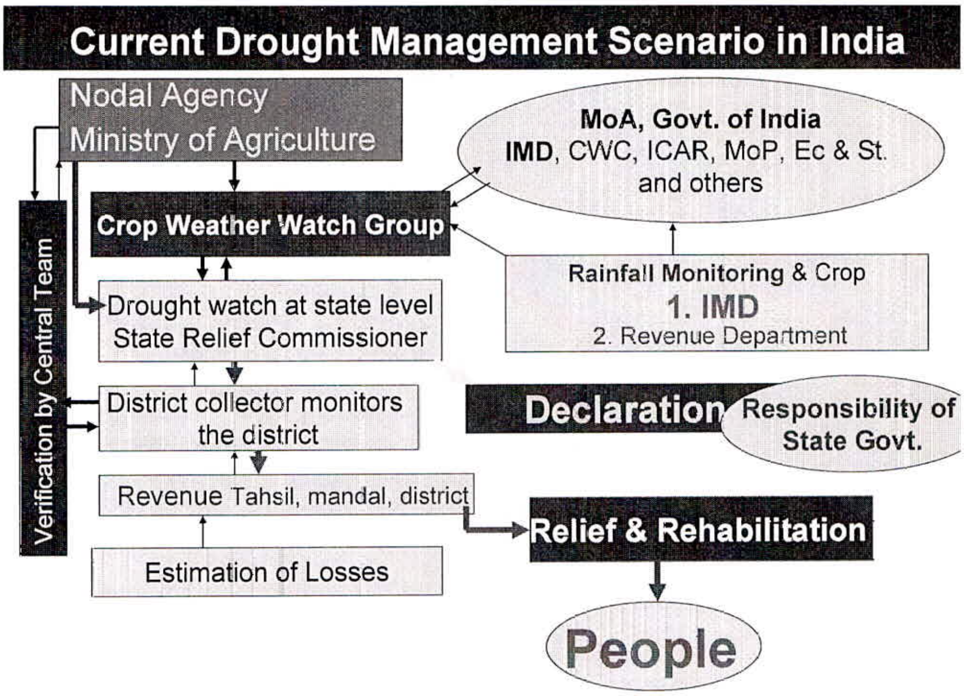
Hence, certain advantages of standardization may be realised by using the series median as the truncation level for drought duration analyses and the series mean as the truncation level for drought severity analyses. However, a complete drought analysis is concerned with both duration and severity but in studying both simultaneously, it is not practical to use two different truncation levels, since each will result in the identification of a different set of drought events. Fortunately, this problem can be avoided by taking advantage of the right skewness of most hydrologic records. In this case, a logarithmic transformation can be utilized to normalize the time series, thereby bringing the mean and median of the transformed series closer together. Since these two measures of central tendency will usually not be identical, even after the logarithmic transformation, it is considered desirable to use a mean truncation level, since the mean is more sensitive to the extreme values of the distribution. In the study of drought events, these extreme droughts are generally of primary interest.

In using the mean of historic series, however, one must be cautions of grossly unrepresentative events included in the sample, particularly if the sample size is small. For example the worst drought in a 30 years record may actually have a recurrence interval of 100 years when viewed in the context of the entire population of events. Because the mean is more sensitive to extreme values, it will be unfairly biased in favour of these values if they are not representative of the population distribution with respect to the available sample size. Thus to use the mean of a series as the truncation level, it is preferable that the historical sample be free of unrepresentatively extreme drought events.

CHARACTERISTICS OF DROUGHT

Droughts are cyclical and regional climatic phenomenon. The Occurrence, progression, severity and impacts of droughts differ from other natural calamities as follows.

1. Drought is a 'creeping phenomenon', making its onset and end difficult to determine. The effects of drought accumulate slowly over considerable period of time and may prolong beyond a period of year(s) for major events.



2. The absence of a precise and universally accepted definition of drought adds to the hesitation about whether or not a drought exists. It is because, the concept of drought definition is conflicting in the literature; it varies according to subject of interest of researchers and among regions of differing climates. This ultimately affects in drought management decisions.
3. The societal impacts of drought are less obvious and extend over the larger geographical area than damages that result from other natural calamities. Drought seldom results in structural damage. For these reasons the quantification of impacts and the decisions for appropriate provision of disaster relief is a far more arduous task than it is for other natural hazards.

Droughts are characterized by their intensity, duration, frequency, and severity. These characteristics form a basis in the planning of management strategies to cope with drought catastrophe in a given place or region. To reduce the impact of drought hardships, it is necessary to understand its characteristics, i.e., its possible duration (How long will it last?), its intensity/severity (How severe will it be?), and its frequency (How often will it recur?). Once these characteristics are known for a given place/climatic region, they can be used as a management tool in the regional planning for drought mitigation (Ponce et al. 2000; Pandey and Ramasastri, 2001).

Drought duration (D) is the period of time when there is a deficiency of precipitation/ stream/soil- moisture preceded and followed by periods when there is no deficiency. A drought event is a series of one or more consecutive drought months/seasons/ years. A drought can have duration of one or more months/seasons or even years. Drought persistence is the tendency of a drought event to last more than one season or year. For instance, a 4-year drought is a very persistent drought.

Drought intensity (I) refers to the magnitude to which actual precipitation/stream/soil- moisture are lesser than the mean or a given threshold value. (i.e. precipitation deficit/ streamflow deficit/

soil-moisture deficit). Drought intensity is nearly independent of the duration and this fact is very well discussed in the literature (Bonacci, 1993; Woo and Tarhule, 1994; Sharma, 1997a).

Drought frequency (F) refers to the number of years that it would take a drought of a certain intensity to recur, in units of year; for instance, once in 10 year. 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 year.

Drought severity (S) refers to the accumulated deficits through out the drought duration (i e. I=S/D). In other words, if one can predict duration and intensity then the severity can be predicted using simple law of multiplication of duration and intensity (Dracup et al., 1980b, and Sharma, 1997b). The drought severity is crucial for hydrological drought while the critical duration even with less severity is important for agricultural drought.

Drought duration, frequency, and severity vary across the climatic spectrum (Gregory, 1989; Dracup et al. 1980a; Ponce et al 2000). The documented experiences on drought indicate that the droughts cause more severe affect in the regions where much of the human activities are concentrated (Lugo and Morris 1982). The experiences reported in literature show that the droughts have tendency to last longer in those climatic regions, which have greater inter-annual precipitation variability (WMO, 1975; Karl, 1983; Johnson and Kohne, 1993; Rasool, 1984). The areas subject to more frequent droughts are those in which variation in annual rainfall are relatively greater (Chow, 1964). Low total precipitation and high variability tend go to hand in hand because, where the total annual precipitation is small, it is generally due to a relatively small number of storms or rainy period. Since the number of events involved is small, it is obvious that the variability will be great. The changes in drought duration across the climatic spectrum point to the regional, rather than local nature of persistence (UNESCO-WMO, 1985). Also, there are several other methods to define drought intensity given in WMO (1989).

Droughts are regional in nature, i.e., they are driven by regional climatic conditions. Therefore, their occurrence is related to regional climatic parameters (Dracup et al., 1980a; Ponce et al. 2000; Pandey and Ramasastri, 2001). The most common climatic parameter is mean annual precipitation, which depends on several factors, among them: (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). The climatic variables at a given location are strongly influenced by the atmospheric circulation pattern (ACP). The researchers have also demonstrated that the ACP plays major role in precipitation occurrence, amount and distribution especially in Temperate Zone (Bogardi et al., 1994). Climatic changes attributable to anthropogenic activities are now being examined throughout the world. There is a wide belief that climatic changes will intensify floods and droughts even before the changes in temperature are severe enough to be noticed (Bruce, 1994; Houghton, 1994).

VULNERABILITY TO DROUGHT

Vulnerability refers to the degree of susceptibility of society to a hazard, which could vary either as a result of variable exposure to the hazard, or because of coping abilities (e.g. protection and mitigation), or both (Anderson, 1994). Even from season to season, vulnerability can vary from extreme crisis to complete safety (Wilhelmi & Wilhite, 2002).

Vulnerability to drought may be assessed considering integrated influence of

(1) climatic components (Precipitation & ET),

(2) hydrological components (surface and groundwater availability in space and time)

(3) Soils

(4) land-use classes/cropping practices

(5) irrigation support etc.

Vulnerability plays crucial role in identifying appropriate actions that need to be taken to reduce adversity before the potential for damage is realized. The assessment of vulnerability to drought for a region/area and discernment of regional drought characteristics (frequency, duration and severity) are more relevant parameter in sizing water conservation and storage schemes towards combating and abetting droughts.

DROUGHT PREPAREDNESS AND MANAGEMENT STRETEGIES

Among all other natural disasters, the drought affects maximum number of peoples in the world and more so in India. Though the occurrence of drought can not be prevented, but being well prepared for its likely occurrence can lesson its impacts on life and plants. Droughts have two basic components- climatic (decrease in precipitation) and demand (use of water). In responding to droughts, governments tend to concentrate most of their effort on reducing the demand of water, although there are limited options for controlling climatic component. Thus, most measures focus on management, reallocation and distribution of existing water resources and on establishing priorities accordingly for different uses. There are commonly known means of combating drought and promoting development (UNCED, 1992) such as:

1. Improving national capabilities, including training and human resource development, for assessing water resources and determining water use on a continuing basis and for the planning and management of these resources;
2. Conserving water resources and optimizing their use;
3. Augmenting the supply of water locally by exploiting surface water and groundwater that might be available in the area, taking into account long-terms trends, the future demands of the local communities, and other needs;
4. Augmenting the supply of water by transfers from more permanent surface water sources (lakes and rivers) and from groundwater resources within arid and semi-arid lands and/or long distance transfers from humid areas if practically and economically possible (and environmentally acceptable).

One of the biggest challenges in successful drought planning is getting all the right groups of people to work and communicate effectively with one another (Wilhite, 1990). Three main groups need to be involved:

1. Climatologists, Hydrologists and others, who monitor how much water is available now and in the foreseeable future.
2. Water Resources managers and others, who determine how lack of water is affecting various interests, such as agriculture, recreation, municipal supplies, etc.
3. High-level decision makers, often elected and appointed officials, who have the authority to act on information they receive about water availability and drought's effects.

All action plans to combat drought must be geared toward the possibilities of extending the availability of water and reducing water demand. Some of the measures of water conservation and augmentation are improved land-use practices, conjunctive use of surface and groundwater, watershed management, rainwater/runoff harvesting, recycling of water, and development of water allocation strategies among competing demands. Storing water in groundwater reservoirs (aquifers) when available can be more advantageous, despite the pumping costs, than surface water storage that may be subject to very high evaporation loss. Drought contingency planning, including restrictions of water use, rationing programs, special water tariffs, and reduction of low-value uses (agriculture), require thorough consideration. Emphasis is being increasingly shifted from water development and providing water in required quantities to the management of finite, scarce freshwater resources. Improvement in efficiency of existing supplies is one of the essential steps to cope with water deficits. Another essential aspect of self-sustaining option is controlling population growth. If there were less population pressure, then activities that increase vulnerability to drought and desertification in less developed countries (over-cultivation, overgrazing, deforestation) could be more constrained (Kundzewicz and Kaczmarek 2000).

In spite of many studies and research activities on drought, the efforts have not been proven enough towards planning and management of drought. There is only few success stories reported in the literature about implementation of measures limiting water use at the time of drought. Drought planning and management system is relatively in advanced stage in few developed countries like Australia, Canada and USA (Wilhite and Wood, 1986). However, in developing countries like India, more efforts are needed for understanding and management of drought problems.

REMARKS

The paper compiles a critical review of the current status of research and development on drought. The concluding remarks can be summarized as follows:

1. Drought duration, severity, time of onset and termination and the areal coverage are the major parameters characterizing a drought event. Selection of the time-unit and truncation level play key role in the assessment of drought duration and severity of a drought event.
2. There exists a variety of techniques and method to analyse meteorological and hydrological drought duration and severity through probability characterization of low flows, time series method, theory of runs, multiple regression, group theory, and neural network methods.
3. One of the deficient areas in drought research is the regional or special behaviour of drought. The special coverage of drought duration and severity is of significant importance in the planning of measures towards mitigating impacts of droughts. The behaviour of droughts in the frequency domain is reasonably well studied using the time series of rainfall and stream flows etc.
4. Methods and techniques to predict onset and termination point of drought are seriously lacking in the literature. Timely recognition of occurrence of drought is a major problem in drought management. An important issue in drought research is to develop a comprehensive monitoring system to collect all relevant data, analyze, and disseminate information in a useable manner.
5. The major challenge in drought research is to evolve suitable techniques for timely recognition of initiation and termination, reliable assessment of characterizing parameters of drought events and improved means to cope with adverse drought impacts.

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