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Challenges in drought research: some perspectives and future directions

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Abstract
There has been a considerable research on modelling of various aspects of drought such as identification and prediction of the duration and severity. The term severity has various connotations in drought literature such as in hydrological drought, it is defined as cumulative shortage or the deficit sum with reference to a pre-specified truncation level. Whereas in meteorological drought, the severity has rather been defined in the form of indices such as Palmer drought severity index, among others. There exist a variety of techniques and methods to analyse the duration and the severity of meteorological and hydrological droughts through probability characterization of low flows, time series methods, synthetic data generation, theory of runs, multiple regression, group theory, pattern recognition and neural network methods. Agricultural droughts are analysed based on soil moisture modelling concepts with crop yield considerations and using the multiple linear regression techniques. The prediction aspects of drought duration are reasonably well developed, whereas the drought severity aspects are yet to be refined because such information is not only of paramount importance but forms an essential and integral part of the design process of storage facilities to combat and abet droughts. A major challenge of drought research is to develop suitable methods and techniques for forecasting the onset and termination points of droughts. An equally challenging task is the dissemination of drought research results for practical usage and wider applications.

INTRODUCTION

Drought means scarcity of water which adversely affects various sectors of human society e.g., agriculture, hydro power generation, water supply, industrial and other allied sectors. The prime cause of drought is the occurrence of below-normal precipitation which is affected by various natural phenomena. Precipitation can be reduced due to, over seeding of clouds by dust particles from earth surface, an increase in albedo, a decrease in the availability of biogenic nuclei for rain drop formation caused by reduced plant cover and similar such factors (Beran and Rodier, 1985). An increase in albedo lowers surface temperatures which in turn decrease lifting of air masses resulting into a reduction in precipitation. Increased albedo also causes local heat loss and the attendant consequential temperature gradient which induces a circulation capable of restoring equilibrium with warmer surroundings and thus inducing subsidence that depresses precipitation. Another important causative factor of droughts is the oceanic circulations. Oceanic water circulations have average patterns of current and heat storage that affect the weather and climate. As an example, on the west coast of South America, there is a north-ward cold current along the shore and a warm current going south towards the Peruvian coast. The two currents are normally deflected westward around the equator, but at irregular intervals over many years they are rather deflected southward and inshore. Such a deflection was observed to happen in 1952, which brought unusual rain to the Peruvian coast and caused wide spread drought in Brazil. Significant climatic variations are known to occur when a warm pool, which is normally present in the western Pacific Ocean, moves eastward towards the coast of Peru. This sea surface temperature anomaly has been referred to in literature as EL-Nino. An El-Nino event in the tropical Pacific Ocean is followed by below normal rainfall and streamflow in the western United States (Kahya and Dracup, 1993). These anomalies emerge mainly due to changes in large-scale atmospheric circulation patterns. The most notable large scale climatic variation that exists from one to another year is the Southern Oscillation (SO), which manifests itself in the differential oceanic temperature phenomenon across the tropical Pacific Ocean. The SO and its interaction with El-Nina is designated as ENSO (EL-Nino Southern Oscillation). The warm phase of ENSO is called El-Nino while the cold phase is called La-Nina. There exists a strong relationship between ENSO and the climate of specific regions worldwide. Manifestations of ENSO are associated to various natural events: recurring wild land fires, fluctuating fish populations, changes in tree ring patterns. Effects are also reflected in hydrologic features such as precipitation and streamflow over the catchments (Piechota and Dracup, 1996).

DROUGHT DEFINITIONS, VARIABLES AND PARAMETERS

W.C. Palmer (1965), a noted authority in the study of droughts, has said "drought means various things to various people depending on their specific interest. To the farmer drought means a shortage of moisture in the root zone of his crops. To the hydrologist, it suggests below average water levels in the streams, lakes, reservoirs, and the like. To the economist, it means a shortage which affects the established economy". Wilhite and Glantz (1985) recognize four types of droughts viz. meteorological, hydrological, agricultural, and socio-economic. However, the first three types of droughts are known more popularly. Meteorological droughts are deemed to occur when rainfall is less than the normal rainfall. Since the deficiency in the rainfall is quickly sensed and noticed, meteorological drought has been the subject of intense study. Definition of hydrologic droughts revolve around the effects of dry spells on surface or subsurface waters. Linsley et al. (1975) considered hydrologic drought as a "period during which streamflows are inadequate to supply established uses under a given water management system". If the actual flow for a selected period of time falls below a certain threshold, then hydrologic drought is considered to be in progression. Such a threshold level can be defined based on the water demand scenario of the place and/or basin under consideration. More objective definitions have been proposed by Yevjevich (1972) and Dracup et al. (1980), and are discussed in the context of the drought parameters. An agricultural drought is considered to have set-in, when the soil moisture availability to plants has been reduced to such a level that it adversely affects the crop yield and hence the agricultural production. In brief, the definitions of agricultural drought hover around the of soil moisture deficiency in relation to meteorological droughts and climatic factors and their impact on the agricultural production.

Time Scales of Droughts

The most commonly used time scale in drought analysis is the year followed by the month (Sen, 1980a, b; Bonnaci, 1993; Sharma, 1997). Although the use of year as a time scale is rather long, it can be used to abstract information on the regional behaviour of droughts. The monthly time scale seems to be more appropriate for monitoring drought effects in situations related to agriculture, water supply and ground water abstractions. For studying the behaviour of short term droughts within a year or a season, the time scale of a day has also been used (Gupta and Duckestein, 1975; Smart, 1983; Zelenhasic and Salvai, 1987; Sharma, 1996).

Drought Variables

A drought variable can be defined as a prime variable responsible for assessing drought-effect, and is considered a key elements in defining drought and deciding the techniques for its analysis. The determinant variable for the meteorological drought is the precipitation/rainfall, whereas for the hydrological drought it is either river runoff/streamflow or reservoir levels and/or groundwater levels. For the agricultural drought, governing variables are soil moisture and/or consumptive use. Therefore, the time-series of the above variables provide the framework for evaluating the drought parameters of interest.

Since the historic record of precipitation and streamflow (river runoff) is generally available at a point, the earlier work on drought analysis has been confined to meteorological and hydrological point droughts, which are referred to a fixed point or a very small region. In case of agricultural drought, the measurement of its determinant factor (soil moisture) is difficult, and hence, the related data sets for historic periods are not available. Such droughts could be best analysed through a complex regional analysis involving a battery of variables (soil moisture, crop yield, leaf area index, vegetative growth etc.) rather than a simple point analysis. In addition, the complexity is further increased by the intricate relationships that exist between the crop yield and soil moisture deficit. Because of such multiple reasons, there have been very limited efforts towards evaluating agricultural droughts. It is noted that the impact of drought on agriculture is not an instant one compared to streamflows or reservoirs.

Drought Parameters

The important parameters quantifying a drought are: (1) duration, (2) severity, (3) location in absolute time, i.e., its initiation and termination time points, and (4) areal coverage. At times, a parameter, namely magnitude or intensity, is also used as merely the ratio of severity to duration (Dracup et al., 1980). The concept of above parameters is illustrated in Figure 1.

The most basic element for deriving the above parameters is the truncation or the threshold level. The threshold or truncation level may be a constant or function of time. In other words, the truncation level specifies the level of water demand in terms of some statistic of the drought variable and serves to divide the time series of the variable in question into "deficits" and "surplus" sections. The parameters of a drought such as duration, severity and intensity are based on the deficit sections. Dracup et al. (1980) defined the truncation level by the expression $x_0=x_m\text{-}e.s=x_m(1\text{-}e.cv)$, where x_0 is the truncation level, x_m, s and cv are the mean, standard deviation and the coefficient of variation of time series of the drought variable x, such as rainfall or streamflow time series, and e is the effective scaling factor. If e is zero, then $x_0=x_m$ i.e. the truncation level is the mean of the series. If one chooses 90% of the mean annual rainfall or runoff (say cv of 0.4), then e=(1-0.9)/0.4=0.25. The corollary of the above expression is that if the time series of a drought variable is standardized (i.e., series of u_i with mean=0 and standard deviation=1) then the truncation level corresponding to mean level would be zero (u_0=0) and that for the 90% of the mean would be -0.25 (cv=0.4). Since the important drought characteristics depend on the truncation level, the selection of a truncation level assumes prime importance in drought analysis. In case of meteorological or hydrological droughts, the threshold can be mean annual precipitation or streamflow respectively. But, such a simple threshold does not serve the purpose of agricultural drought analysis.

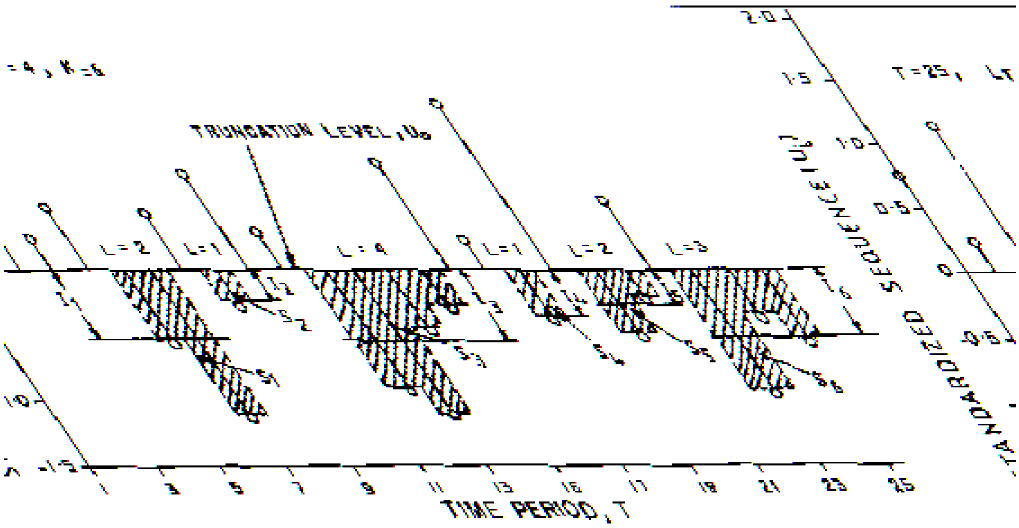

Figure 1. Definition Sketch of Drought Parameters.

The truncation level can be assigned a probability quantile such as q=P(x# x_0), where q is the probability of drought corresponding to the truncation level x_0 and P (..) stands for the notation of the cumulative probability. The drought probability q is dependent not only on the truncation level but is also a function of the probability distribution of the drought variable (Yevjevich, 1972; Sen, 1980a). Sharma (1997) has suggested a simple analytical method for determining the drought probability quantile (q) corresponding to a truncation level for Normal, Log-normal and Gamma distributions of the drought variable. Some researchers (Horn, 1989; Frick et al., 1990) have studied the effect of truncation level on drought parameters through simulating sequences of the drought variable and then truncating them at the desired level. The drought parameters are derived based on the deficits encountered in the simulated sequences.

Drought Severity Indicators

Although terms i.e., duration, time points of initiation and termination of drought, and the areal coverage have been defined in nearly consistent manner in the literature, a considerable disagreement exists in defining the term severity. In the literature of meteorological droughts, the severity has been expressed through some indices. Through the analyses of dry spells using monthly rainfall records in Australia, Foley (1957) suggests a drought severity index. The residual mass curve technique was used for developing this index. Other more objective indices such as decile range (Gibbs and Maher, 1967) and the standardized indices (Gibbs, 1975) have also been introduced in subsequent years. The best known index is the PDSI (Palmer drought severity index), which was proposed by Palmer (1965) from the US Weather Bureau. Since its inception, PDSI has evolved into numerous modified versions. For example, Karl (1986) has described a modified version known as the Palmer hydrological drought index (PHDI), which is used for water supply monitoring. The other index parallel to PDSI is the standardized precipitation index (SPI) (Guttman, 1998). It has been shown that the values of PHDI are highly sensitive to errors in the precipitation values, whereas SPI has the potential to be a superior and yet simpler index of drought severity over PDSI (Guttman, 1998).

In the context of hydrological droughts, Yevjevich (1972), and Dracup et al. (1980) defined the severity as the cumulative shortage or deficit sum with reference to a desired truncation level, and therefore the severity has the unit of mm or cubic metres. After a threshold is selected, a drought severity analysis can be conducted based on the drought duration as a function of the selected threshold level. The severity of drought is a function of the drought duration and probability distribution of the drought variable and its autocorrelation structure. The frequency analysis of critical droughts is helpful in deciding a design criteria in many water resources projects (i.e., hydrological drought), and the selection of a cropping system or pattern (i.e., agricultural drought). The longest duration and the largest severity can be taken as the statistics for critical drought (Sen, 1980a; Sharma, 2000). The severity is crucial for the hydrological drought while critical duration even with less severity is important for agricultural drought.

Regionalization of Droughts

In general, the regional behaviour of droughts has been studied by analysing the point behaviour (i.e. data analysis of point rainfall or streamflow) and then mapping the relevant parameters over a region or a country. For example, the isoline maps of 1 in 10, 1 in 50 , 1 in 100 or 1 in 500 year frequency droughts at the defined truncation levels or the drought severity indices as those of Palmer or Herbst et al. (1966) can be drawn. Horn (1989) drew maps for the longest durations and the largest severities for 1 in 100 year droughts for the state of Idaho in the USA based on the point analysis of the annual flow data of 63 rivers.

Some efforts are underway at the regional analysis of droughts through stochastic approaches and an excellent review has been made by Rossi et al. (1992). Tase (1976) and Sen (1980c) have advanced the idea of analysing regional droughts using the notions of random fields. Santos (1983) extended the concepts of random fields and investigated the regional characteristics of drought. One important tool which is indispensable in the regional analysis is the multiple regression algorithm (Paulson et al., 1985; Mimikou et al., 1993, Kumar and Panu, 1997) which involves drought parameters, geomorphic parameters and climatic parameters for the development of regression equations. Another important tool for regionalisation is that of kriging (Chang, 1991). Based on group theory, other emerging approaches for drought analysis are pattern recognition (Kumar and Panu, 1994) and neural networks (Shin and Salas, 2000).

METHODS AND TOOLS FOR DROUGHT ANALYSIS

The identification and prediction of droughts are achieved through analyses of time series of drought variables such as rainfall, streamflow, and soil moisture data on a variety of time scales. At times, data series can be generated stochastically or through physically based concepts such as water balance or soil moisture accounting procedures. For example, the PDSI data can be generated using soil moisture accounting algorithm (Palmer, 1965). Proxy data such dedrochronology (i.e., tree-ring), mud varves, ice coring, palynology (i.e., pollen analysis), paleonotology (i.e., continental and marine fossil), geological movements, sea-level fluctuations, and paleomagnetic data could also be invoked in the analysis and synthesis of long-term droughts (Chin, 1973). Of such data sets, the most commonly used are those of tree-rings. The identification and prediction methods of droughts commonly invoked on derived or generated data sets are as follows.

[1] Frequency or Probability Based Methods: In these methods low flows or low flow volumes during a specified period are analysed in a manner similar to that of flood peak analysis (Joseph, 1970; Yevjevich et al., 1978; Clausen and Pearson, 1995).
[2] Regression Based Methods: Regression analyses have been conducted to relate drought parameters with geomorphic and/or climatic factors, crop yield factors, and other relevant factors for prediction of duration and severity of droughts (Paulson et al., 1985; Mimikou et al. 1993; Kumar and Panu, 1997).

[3] Theory of Runs Based Methods: The probabilistic structure of drought durations (run length) and severities (run sum) are analysed using the notion of runs (Yevjevich, 1972). In these methods, the drought parameters such as the longest duration and the largest severity are analysed. The analysis is carried on the time series of random or Markovian drought variables (Sen, 1980; Sharma, 2000). Another approach within this category of models is the use of discrete autoregressive and moving average (DARMA) processes to model the variability of wet and dry years (Chung and Salas, 2000).

[4] Group Theory Based Methods: The characteristics of droughts in terms of their durations and lengths can be expressed as groups and cluster of groups. In turn such data sets can be analysed to develop drought prediction and forecasting techniques utilizing the concepts of pattern recognition (Kumar and Panu, 1994) and neural networks (Shin and Salas, 2000). However, group theory based methods are still in initial stages of development.

[5] PDSI Based Methods: The time series of Palmer drought severity indices (PDSI) are synthesized to identify and characterize the severity of droughts. Since PDSI series display a Markovian structure, such indices and their derivatives have been the focus for forecasting of agricultural droughts (Lohani and Lognathan, 1997).

[6] MAI Based Methods: The moisture adequacy index (MAI) is a measure of the degree of soil-moisture availability for plant growth. The Food and Agriculture Organization of

the United Nations has developed an algorithm to generate MAI times series for characterization of agricultural droughts and their severity (Kumar and Panu, 1997).

DROUGHT FORECASTING: STATE OF THE ART

The behaviour of droughts in the frequency domain is reasonably well studied using the time series of rainfall and streamflows etc. However, the forecasting aspect is more important from the point of view of drought preparedness and early warning, which is still fraught with great difficulty. In terms of the long-term forecasting of the droughts, some studies are underway by correlating the time series of PDSI, precipitation, temperature and streamflow with the ENSO events (Piechota and Dracup, 1996; Cordery and McCall, 2000). The variables based on ENSO events are southern oscillation index or sea surface temperature. The other useful correlative variable that has been identified is the geopotential height, which seems to offer potential in forecasting drought periods in association with southern oscillation index (Cordery and McCall, 2000). On a short time scale, such as a month or a season, some possibilities exist to indicate the probable timings of inception and termination of drought (Beran and Rodier, 1985). Chang and Kleopa (1991) indicate that drought monitoring offers a means of providing some clues on the short-term forecasting. Short-term forecasts essentially employ one or more combinations of the following procedures.

(1) Linear regression models involving weather variables such as, air pressure, air and sea surface temperatures, wind velocities and directions, and the recent record of the precipitation data are used for drought prediction. In the area of agricultural droughts, regression models involve crop yield, weather variables such as precipitation of the recent months, number of wet days and similar correlative variables (Kumar and Panu, 1997), which are of greater significance.

(2) Teleconnections, which are links between sea surface temperatures and inland weather, wind in east Africa, and monsoon in India, location of ITCZ (inter-tropical convergence zone), jet streams, El-Nino, etc., form the basis of drought forecasting (Cordery and McCall, 2000).

(3) Time-series forecasting algorithms employing the notions of ARIMA models, non-homogeneous Poisson processes coupled with conditional probabilities have been used for short-term forecasting (Lohani and Lognathan, 1997).

(4) Recession rates of streamflow hydrographs, stage graphs of other water bodies, and indices based on the status of soil moisture and vegetation in the region under consideration have been used for short-term forecasting (Zelenhasic and Salvai, 1987).

There is a potential in forecasting the droughts based on the behavioural patterns monitored during the past droughts. Several indices based on hydro-climatic, vegetation, ecological, environmental factors need to be monitored for reliable and robust forecasts of the droughts. The statistical and mathematical algorithms of forecasting are reasonably well developed, whereas the phenomenal and causative aspects are far from being satisfactory. One major application of the drought forecasting is in planning the measures to mitigate the impacts of drought by the governments and the related agencies. It is noted that droughts are merely normal occurrences in climatic systems and not just the extremes. It is in this perspective that the preparedness and planning for droughts has to be risk based rather than the crisis based, as is the practice today in most countries. The forecasting aspects of droughts is therefore of utmost importance, if we are to adopt the risk based approach to combat and abet the effects of episodes of drought.

CONCLUDING REMARKS

[1]. The major cause of droughts is some anomalies in the weather or climate that lead to less rainfall or precipitation than normal for meeting water demands in agriculture, industry, households, hydro-power generation, recreation etc.

[2]. Precipitation and streamflow are measurable and their historic records are normally available, therefore earlier hydrological and/or meteorological drought analyses were made on point data sets, which are site specific or applicable to a small area. Statistical techniques used in drought analysis range from simple probabilistic and frequency analysis to complex generation of probability density functions of drought characteristics (such as duration, severity) utilizing the concepts of run theory, DARMA models, group theory. Some of the assumptions underlying these techniques are of independent events, stationary processes, Bernoulli trials, Markov chains etc. Most of the techniques use annual data and therefore, a year is the minimum time scale of their prediction. Some synthetic data generation models emphasize at multi-year droughts. These models need to be transposed for the drought analyses on short time basis such as month, week or even a day.

[3]. Statistical techniques dealing with the duration aspects of drought are reasonably well developed whereas techniques for severity aspects are some what lacking and require considerable improvement and refinement. Interestingly, still the researchers are more concerned with duration aspects rather than the severity of droughts. The severity has been identified by many researchers to be more relevant parameter in sizing storage reservoirs towards combatting and abetting droughts (Sen, 1980; Sharma, 2000).

[4]. Agricultural droughts are areal in nature and affect the production of basic necessities i.e., food and fodder, and thus are more likely to affect the economy of the region. Since the total annual precipitation is not as significant an indicator of agricultural drought as the distribution of precipitation during the crop growing season, the use of in-situ statistical methods of hydrological drought analysis require modifications for the analysis of agricultural droughts.

[5]. A few indices of agricultural droughts have been developed. One of the earliest indices is the Palmer drought severity index. Although Palmer developed it for meteorological drought but intrinsically it refers to agricultural drought. There has been no agreement on the effectiveness of this index in varying climatic regions. The weekly moisture adequacy index based on the FAO method of water balancing can be examined for its feasibility as a parameter in statistical forecasting of agricultural droughts. Also, the pat-

tern recognition techniques need investigations for their incorporation to strengthen the development of agricultural drought monitoring and early warning systems.

[6]. In agricultural drought, the establishment of a functional relationship between the crop yield and a parameter reflecting soil moisture deficit is of utmost importance. The development of this relationship can be attempted through the use of pattern recognition techniques. A pattern of optimum or expected yield could be developed and the permissible variation in each variable would be determined. Based on the development of such variables and utilizing the concepts of conditional probabilities, a method of short term prediction of drought could be formulated.

[7]. Another deficient area in the drought research is the regional or spatial behaviour of droughts. Analogous to regional flood frequency analysis, there is a need to coin the phrase "regional drought frequency analysis". The spatial coverage of drought duration, severity and/or intensities is of significant importance in planning the measures towards mitigating impacts of droughts.

[8]. It is known that the drought is a creeping phenomenon. It is rather easy to sense that the drought has set in, particularly during a cropping season. There is a need to develop methods and techniques to forecast the initiation and/or termination points of droughts. The ARMA models, pattern recognition techniques, physically based techniques on PDSI, PHDI, and SPI, or moisture adequacy index involving Markov chains or the notions of conditional probability seem to offer potential to develop reliable and robust forecasts towards this goal. Such research efforts would be of considerable importance in mitigating the impacts of agricultural droughts and /or short term hydrological droughts.

[9]. In the domain of droughts, most of the research developments are still confined to technical journals. A little has appeared in the hydrological texts meaning that either the subject matter of the drought analysis is too complex or still debatable. Therefore, there is a need to make the drought research amenable to practitioners engaged in drought monitoring, forecasting, and management operations.

[10]. Droughts are perceived as extreme events in the climatic systems, whereas in reality they need be recognised as normal occurrences. Drought impacts, therefore, should be handled using the risk based approach rather than the crisis based approach, as is the practice today in most countries.

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