A Review of Some Methods used for Drought Identification and Analysis

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Abstract

Water management under extreme hydrologic conditions such as drought is a challenging issue to hydrologists, engineers and environmental scientists. To ensure sustainable management of water during drought periods and to adequately resolve various issues related to drought occurrence and management at various scales, it is important that suitable methods and procedures for drought identification and analysis be known. Examining the available techniques can do this. In this paper, some of the methods that can be used to identify and analyse drought are reviewed. Although several methods are available for drought identification and analysis, it is noted that not a single technique can be used for all drought types and in all circumstances and that for various drought types, it is necessary that they be identified and analysed using a combination of different techniques.

Key words: D*rought; drought events; truncation level; Markov process*

1. Introduction

With increasing population and the demand for water supplies for various functions such as municipal, irrigated agriculture and productions of good and services, there is need for successful operation of water resource systems. This depends on the management of the system under extreme hydrological conditions such as the occurrence of droughts. Droughts are frequent worldwide and affect both developed and developing countries. Unfortunately there are not reliable methods and procedures for their identification and analysis (Bonacci, 1993). Besides, there are many views as to what exactly constitutes drought since various researchers and professionals from different scientific disciplines use different approaches in the identification and assessment of the drought phenomenon.

Many attempts have been made to resolve the issue of drought identification but conclusions from these undertakings have been divergent and far from unanimous. For instance, Yevjevich *et al.* (1977) observed lack of agreement on the definition and methods of drought description and identification and noted the availability of many methods that yield different results. On the question of what actually drought is, Grigg (1989) discussed the dilemma of classifying drought either as a disaster or hazard the solution of which is vital in the management of water resources during drought periods while Wendland (1990) observed that drought exists when water demand exceeds supply for an extended period. However, drought perception is a function of several factors such as the sensitivity of an activity to water availability, the time of the year and the magnitude of the deficit relative to some expected value.

Since drought is a manifestation of hydroclimatological, meteorological and agro-climatological variations in space and time, drought management requires knowledge of its various characteristics including onset, duration, severity and, areal extent. This is in view of the fact that with increasing human and livestock population and the corresponding increase in demand for additional water supply for either municipal, irrigated agriculture or hydropower production, there is need to manage water resource systems under conditions of severe water deficits. To this end, various methods and procedures have been proposed and developed for purposes of drought identification and analysis. The purpose of this paper is to review some of the available methods that may be used in the identification and analysis of drought.

Drought may be defined from various viewpoints based on different disciplines. Hydrologically, drought may be viewed as below average water levels in streams, lakes and reservoirs and defined as periods when flows fall below a specified truncation or demand level (Dracup *et al*., 1980; Zelenhasic and Salvai, 1987; Van Lanen *et al*., 1997). Such a drought can have serious implications to communities that depend on rivers for water for various functions such domestic, irrigation, hydropower production and for municipal uses. Therefore, information on hydrological drought is useful in planning for activities that rely directly on water from streams for farming, livestock production and water supply for domestic purposes (Ben-Zvi, 1987; Woo and Tarhule, 1994).

Meteorologically, drought is said to occur when rainfall fall below a range of values and are often defined on the basis of degrees of dryness and durations of the dry periods while agriculturally, various characteristics of meteorological drought are linked to agricultural impacts focusing for instance on rainfall shortages, departures from normal or numerous factors such as evapotranspiration (Wilhite and Glantz, 1985). An agricultural drought is said to occur when soil moisture availability drops such that it adversely affects crop yields. This then implies that agricultural drought definitions revolve around deficiencies of soil moisture with respect to meteorological droughts and climatic factors and their consequent effect on agriculture. Definitions that express features of the socio-economic effects of drought may also incorporate features of meteorological, agricultural and hydrological drought and are usually associated with supply and demand of some specific economic good.

2. Factors to Consider in the Identification of Drought

Drought can be quantified using various factors such as initiation and termination, duration and severity. In identifying drought at a particular location or site, several steps should be considered. They include determining the nature of the water deficit or the characteristic drought indicator, identifying the drought variable and the integral period of time and selecting the truncation level that separates the drought events from the rest of the hydrological time series (Dracup *et al*., 1980). The water deficit can be defined using several indicators such as runoff, recurrence interval, evapotranspiration deficit, average depth of groundwater, tree rings or lake and reservoir heights, among several others. Some of these indicators have been used by various researchers including Pandzic and Subaric (1984); Dracup and Kendall (1988); Stockton (1988); Chang and Stenson (1990); Wendland (1990) and Mohan and Rangacharya (1991).

Even though drought occurrence in an area may be examined using either rainfall or streamflow as a drought characteristic indicator, rainfall deficit is the main cause of drought in an area and other characteristics such as hydrological, hydro-geological, agro-climatological and/or their combinations are more or less directly influenced by the spatial and temporal variations of precipitation. However, this does not necessarily mean that only rainfall should be considered as the main drought indicator since drought is such a complex phenomenon that can only be understood and explained using a combination of several factors including hydrology, geology and other catchment characteristics.

3. Time Increment for Drought Analysis

Generally, the hour, day, month, season or year over which the hydrological time series are averaged may be used as the time increment in the drought analysis although the month and year are the most commonly used in drought analysis. The month time unit is long enough to eliminate the less significant and extreme events and is short enough to allow for the monitoring of drought effects in agriculture, water supply and groundwater levels. On the other hand, the year works well for regional drought analysis although it has limitations due to loss of information since it is too long. It is also problematic for synthetic droughts of given return periods where generation of longer sequences of drought events is required, since annual discharges of subsequent years are not well correlated. Several studies have used daily discharge and rainfall to identify and analyse drought occurrence in various parts of the world (Zelenhasic and Salvai, 1987; Mohan and Rangacharya, 1991 and Bonacci and Stambuk, 1991).

4. The Truncation Level to Use

The truncation level (or threshold approach) is applied in drought analysis by most researchers and it is generally agreed that drought occurs when the chosen characteristic is either equal to or lower than the truncation level of drought, X_{TL} (Ozga-Zielinska, 1989). According to Dracup *et al.* (1980), the truncation level may be expressed as shown in equation (1).

$$X_{TL} = \overline{X} - E\sigma \tag{1}$$

where, $\overline{X}$ is the series mean, σ is the series standard deviation and E is the effective scaling factor.

Although the truncation level is usually chosen as a measure of the central tendency of the drought sample and can either be mean, median or mode, other criteria based on the hydro-meteorological, logical and economic considerations of an area may be used in selecting the truncation level (Ozga-Zielinska, 1989). Since the truncation level used influences the results of a drought analysis as well as its identification, it is important to apply various criteria and different truncation levels to be able to draw appropriate conclusions from a particular drought study.

5. Approaches Used for Drought Definition and Analysis

Several methods are available for the identification and characterization of the drought phenomenon. The various methods are generally based on various approaches such as frequency or probability, regression, runs, group and various indices such as the Palmer Drought Severity Index (PDSI) or the Moisture Adequacy Index (MAI), Standardized Precipitation Index (SPI) and pattern recognition techniques. Details of these methods are available in various publications such as McKee *et al.* (1993, 1995), Kumar and Panu (1994), Lohani and Lognathan (1997), Kumar and Panu (1997), Dalezios *et al.* (2000), Sharma (2000), Chung and Salas (2000) and Shin and Salas (2000). The results from the different methods differ and so the choice of which method to use should be based on the type of drought being examined and also on practical, logical and physical considerations. Also, the nature, size and reliability of the data should be taken into account since some index-based methods like the Palmer require different primary hydrometeorological data types besides the fact that it is fairly complex.

In the literature, a variety of approaches are available for analysing drought events (that is, duration, severity and magnitude) using a hydrological or meteorological time series. The approaches include use of frequency and time series analyses, synthetic data generation methods, the theory of runs, multiple regression, group theory, pattern recognition and neural network techniques. Some of these methods are in their initial stages of development and have not been fully developed. The techniques for under some of the approaches are the runs, discrete Markov, the percentile and Herbst's procedure (Herbst *et al.*, 1966; Yevjevich, 1967). Others are Palmer's index and the theory of a random number of random variables (Palmer, 1965 and Zelenhasic and Salvai, 1987).

6. Runs-based Approaches

The runs method is based on the theoretical hypotheses of Yevjevich (1967) whereby a run is defined as a succession of similar observations preceded and succeeded by one or more different observations. It allows for the analysis of the probabilistic structure of critical drought events using a time series of random or Markovian stream flow or rainfall as basic drought variables (Sen, 1976, 1980, 1990; Sharma, 2000 and Panu and Sharma, 2002). Using the runs method, a drought has three main components namely; duration, T; magnitude or intensity, M (average water deficiency) and severity, S (cumulative water deficiency). These three drought attributes are known as drought events and Figure 1 shows the basic concept of the runs technique as applied to drought analysis.

In Figure 1, W represents the surplus of the drought parameter while the shaded portions indicate the deficits or severities. It should be noted that the three drought events characterize drought in different ways and that once T and S are known, M can be obtained from the ratio of S to T (Bonacci, 1993). Also, there is a strong relationship between T and S. Zelenhasic and Salvai (1987), Chang and Stenson (1990), Bonacci (1993) and Agwata (2005) have found strong and statistically significant correlations between duration T and severity S for daily, monthly and annual rainfall and flow data confirming the relationship between the two drought events. Although there is some correlation between *T* and *M*, it is weak and statistically insignificant whereas that between severity S and magnitude *M* is fairly high but not as strong as the correlation between *T* and *S*.

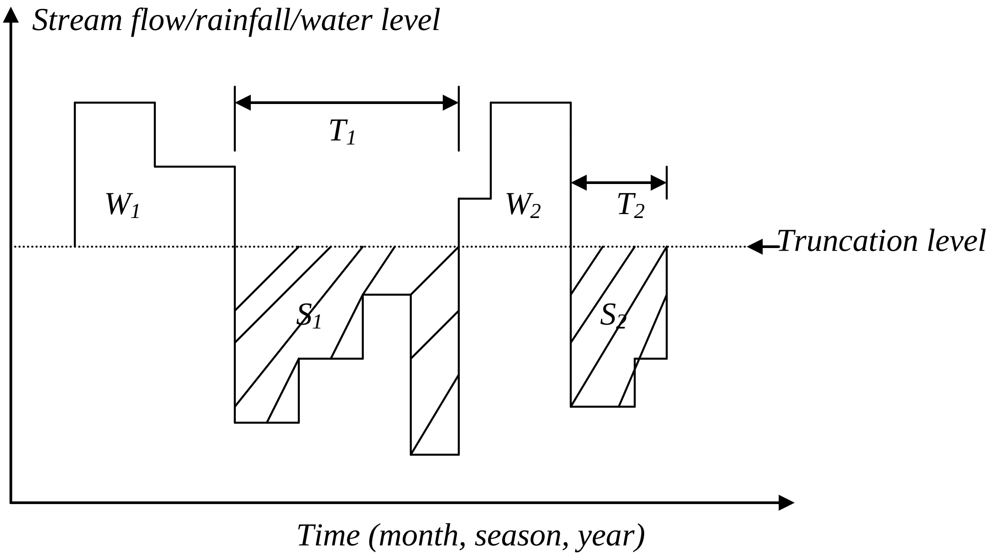

Figure 1. Schematic representation of drought parameters

A large number of recent studies that have made use of the runs approach to examine drought events in various parts of the world include work by Sharma (1994), Woo and Tarhule (1994), Clausen and Pearson (1995), Madsen and Rosbjerg (1995), Tallaksen *et al.* (1997), Sirdas and Sen (2003) and Bayazit and Önöz (2005), among others. The runs approach is popular because it characterizes the drought variable in terms of duration and severity or deficit volume and provides an objective definition of droughts (Tallaksen *et al*., 1997). The runs approach also has practical applications especially in the design of water storage structures such as reservoirs or when there is need to permit water abstractions from water sources. However, the technique only serves well for drought occurrence at a single site and so when time series of the drought variable at two or more sites are considered, the method performs poorly and an alternative procedure is required (Bayazit, 1981). The discrete autoregressive and moving average processes is another runs-based procedure whereby the variability of periods of surplus and deficits of the drought variable are modelled (Chung and Salas, 2000).

7. The Drought Index-based Approaches

A drought index is one that gives a quantitative estimate of drought severity and its development involves the selection of the nature of water deficit to be studied, the averaging period to be considered, the truncation level to be applied to separate drought from the remainder of the time series and the method of regionalization (Dracup *et al.*, 1980 and Oladipo, 1985). The available indices are meteorological-, agricultural- and hydrological-based and include the decile index, standardized precipitation index, Palmer drought severity index, crop moisture index, surface water supply index, the reclamation drought index and the Bhalme and Mooley drought Index (Panu and Sharma, 2002). Other researchers that have reviewed and evaluated the performance of some drought indices include Oladipo (1985) Srikanthan (1993) and Agwata (2005).

The time series of a drought variable are subjected to different indices and used to identify and characterize the severity of droughts. For example, using the Palmer index, the severity series are useful in forecasting agricultural drought in large areas. The index is popular and widely applied in drought monitoring because it provides decision makers with a measurement of the abnormality of recent weather for a region; places prevailing conditions in historical perspective and displays well the spatio-temporal characteristics of historical droughts (Alley, 1984). The index is also most effective in measuring impacts sensitive to soil moisture conditions, such as agriculture and as a useful drought monitoring tool in terms of actions related to drought contingency plans (Willeke *et al.*, 1994).

8. Frequency–based Approaches

Frequency based approaches make use of low flows of a fixed duration. Normally, the 1-day, 7-day or 10-day durations are used in the analysis of drought. The mean annual minimum approach is also used but only when the magnitude of a drought duration is of interest. Some times, drought durations based on the truncation levels are modelled using various frequency distributions. Some of the regional drought studies that have used this approach include those by Hayes (1991), Gustard *et al.* (1992), Gustard and Irving (1993), Woo and Tarhule (1994), Pearson (1995) and Kjeldsen *et al.* (2000). Stedinger *et al.* (1993) have provided a comprehensive review of the frequency-based methods.

9. Group-and Regression-based Approaches

These approaches are based on the fact that drought durations can be clustered into groups that can be analysed so as to develop prediction and forecasting techniques by using the pattern recognition methods and neural networks (Kumar and Panu, 1994; Shin and Salas, 2000). It should be noted that the group-based approaches are in their development stages and have not been widely applied in drought analysis. The main focus of the regression-based methods has been to relate drought events with various factors such as the climatic (El Nino Southern Oscillation), geomorphic, agricultural yield and others for purposes of the prediction of drought duration and severity. Some of the studies that have applied these procedures include those by Clausen and Pearson (1995), Kumar and Panu (1997), Van Lanen *et al.* (1997) and Pongracz *et al.* (2005), among others.

According to Sen (1976, 1990), the drought characteristics of a phenomenon depend on the underlying generating mechanism and may be suitably modelled using a stochastic process such as an independent, first and second-order Markov process. In the Markov process the idea is not to define the statistical characteristics of drought but to find the critical deficits that are preceded by insignificant surpluses using an arbitrary number of classes or groupings, which have either similar probability or different probabilities. The same procedure is followed in the case of surplus classes, which appear in the step preceding the deficit and can be performed or repeated for second or third order Markov process and is performed to for those deficits actually represent critical cases.

10. Regional Drought Analysis

The analysis of drought over a region requires investigations based on basic hydrologic data or various methods of analysis and most of the available work revolve around the description of characteristics of historical droughts over a region such as areal coverage using different types of maps, estimation of drought characteristics over a region in terms of probability of occurrence through direct derivation of probability distribution functions using available time series of basic variables or derived drought indices, estimation of regional drought characteristics through stochastic models of spatio-temporal variability of drought indices and regional estimation of low flow characteristics including the use of relationships between low flow indices and climate and physiographic characteristics. Rossi *et al.* (1992) has provided an excellent account of the procedures for analysing regional drought.

Analysis of historical regional drought requires the examination of spatial variability of a basic variable or a drought index and several procedures are available to do this. The first method for estimating spatial variability in regional drought studies is the isoline maps which are developed using various descriptors such as rainfall depth at a given time interval, rainfall deficit and standardized deficit obtained as the ration of precipitation deviation from the mean over standard deviations. Regional droughts may also be estimated using stochastic models for which the general approach is to develop the mathematical model, formulation of regional drought indices, and analysis of statistical properties of drought indices using analytical procedures. In using the regional estimation of low flow characteristics, probability distribution functions such as the three parameter log normal, the Pearson Type III and IV distributions and the Weibull distribution that best fit the historical frequency distribution of a drought variable is defined for durations such as 7, 10, 15, 30 or 45 days.

Of the procedures for regional drought analysis, there is none currently available for predicting accurately the time occurrence of drought duration or areal drought extension. The techniques available for analysing quantitative relationships between various drought characteristics at regional and temporal scales include the multiple regression analysis or the Monte Carlo simulation techniques as demonstrated by Horn (1989) and Lee *et al*. (1986) who examined spatial variability and frequency analysis of droughts.

11. Forecasting and Prediction of Drought

Drought forecasting and prediction is critical in terms of drought preparedness and early warning to reduce the impact associated with drought occurrence. Although there are still challenges associated with procedures for drought forecasting, several attempts have been made to correlate time series of some drought indices (such as PDSI) and drought variables of precipitation, stream flow and temperature with the Southern Oscillation Index and/or sea surface temperature and geopotential height (Piechota and Dracup, 1996; Cordery and McCall, 2000). Drought forecasting and prediction on the long term is still riddled with various challenges in terms of appropriate procedures and data requirements although teleconnnections linking sea surface temperatures with several weather parameters such as wind, the Inter-Convergence Zone, jet streams and the El Nino phenomenon have shown promise for drought prediction and forecasting (Cordery and McCall, 2000). On the short term, forecasts and predictions of drought are based on various procedures including use of linear regression models, time series forecasting algorithms, recession rates of discharge hydrographs, soil moisture and vegetation indices (Zelenhasic and Salvai, 1987; Kumar and Panu, 1997; Lohani and Lognathan, 1997). There is still potential for using methods based on behavioural patterns of historical droughts using hydrological, climatic, vegetation, and environmental based indices for forecasting of drought to ensure effective planning of mitigation measures to avoid crisis-based management and planning of drought as is usually the practice. Other methods that have potential for drought forecasting and prediction are those based on remote sensing techniques particularly for large areas affected by drought.

12. Conclusion

Techniques for drought identification and analysis are many and vary in terms of data needs, complexity, nature of drought being examined and whether the analysis is at a site or an area. The methods range from simple frequency analysis to complex generation of frequency distribution functions of drought duration, severity and magnitude or intensity. The methods are based on various concepts such as the run theory, autoregressive and moving averages modelling techniques, group methods, and pattern recognition and drought indices. The time increment used will often depend on the study focus but would be annual, seasonal, month or even day. Some of the methods such as the group- and pattern-recognition and neural networks-based are being developed and their scope of application is limited but there is promise in their wide application in the future.

Since droughts are hydrological extreme events that have occurred in the past and will continue to occur in the future, there is need to continue research on these events in terms of their impacts on water resources and other water resources systems for sustainable management of the resources and for continued socio-economic development. Continued drought research will require refining available techniques and procedures and developing new techniques and methods for drought identification and analysis to enable effective planning and management of drought and the associated impacts.

The inadequate understanding of the concept of drought in terms of what it really means and the apparent lack of preparedness and planning for mitigation of its physical and social impacts has serious global implications for the future in terms of water management and food production and consumption patterns. There is need therefore to refine current identification and analysis techniques and to develop new appropriate ones for forecasting and predicting drought occurrence for purposes of implementing strategies that minimize associated impacts.

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