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On the Definition of Droughts

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In this paper, several considerations for developing a practical, analytical definition of droughts are discussed. These considerations include (1) selection of the nature of the water deficit to be studied (hydrological, meteorological, or agricultural); (2) selection of the averaging period used to discretize a continuous time series (months, seasons, or years); (3) selection of the truncation level used to separate droughts from the remainder of the time series (mean or median); and (4) method of regionalization or standardization. These decisions are discussed in terms of their impacts on various approaches to drought frequency analysis. In this paper, drought events are considered to be composed of duration, magnitude (average water deficiency), and severity (cumulative water deficiency). An application of the proposed drought definition procedure is presented for the case of a frequency analysis of multiyear hydrologic droughts.

INTRODUCTION

An essential first step in a scientific analysis is to clearly define and specify the components of the problem under investigation. This requires isolating the problem from other associated issues and formulating nonambiguous definitions of the important concepts. Certainly, the study of drought events is of no exception. It is obviously necessary to decide exactly what is meant by the term 'drought' before any proposed analysis can be developed and utilized. In the current hydrologic literature, devising a suitable universal definition of drought events has proven to be an abstruse task. *Yevjevich* [1967] has stated that the failure to develop a succinct and objective definition of droughts is one of the principal obstacles to the effective investigation of these events.

In a broad sense, the problem of drought definition is caused by the conflicting concepts held by a variety of academic fields of study. For example, the hydrologist is concerned with drought in the context of a period of below normal streamflow and depleted reservoir storage; the meteorologist is concerned with drought in the context of a period of below normal rainfall or snowfall; the agriculturalist is concerned with drought in the context of a period during which soil moisture is insufficient to support crops; and the economist is concerned with drought in the context of a period of low water supply which affects society's productive and consumptive activities. In addition, the concept of drought varies among regions of differing climates. In Bali, any period of 6 days or more without rain is considered a drought, while in Libya, droughts are only recognized after 2 years without rain [*Hudson and Hazen*, 1964].

Although the preceding drought concepts differ in many ways, they all require the analyst to consider a certain set of decisions in order to accurately define the type of drought event to be studied. This set of decisions consists of the following:

(1) Is the primary interest in precipitation (meteorologic drought), streamflow (hydrologic drought), or soil moisture (agricultural drought)?

(2) What is the fundamental averaging period of the time series to be studied (e.g., month, season, or year)?

(3) How are drought events distinguished analytically from other events in the time series?

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(4) How are the regional aspects of droughts to be considered in the study?

This paper deals with the implications of each of these questions as they relate to the issue of drought definition. The specific decisions made by an analyst will be a function of his point of view and the intent of his analysis. The choices available are identified, and the impacts of various alternative drought definition decisions on possible analyses to be performed are discussed. A drought definition is then selected to be utilized in the frequency analysis for multiyear hydrologic droughts.

In this paper, droughts are considered to have three components—duration, magnitude (average water deficiency), and severity (cumulative water deficiency). The implications of the definition of drought upon these three parameters will be evaluated herein.

THE NATURE OF THE WATER DEFICIT

The initial decision which must be made in determining a particular definition of drought concerns the nature of the water deficit, which will be of primary interest in the study. As previously stated, this deficit may be related to streamflow, precipitation, soil moisture, or any combination of the three. Although a complete analysis of a drought event would necessarily include consideration of rainfall, runoff, and soil moisture together, most drought studies have focused on only one aspect of the drought phenomenon [*Whipple*, 1966; *Beard and Kubik*, 1972; *Herbst et al.*, 1966; *Gupta and Duckstein*, 1975].

Selecting the nature of the water deficit to be studied in turn determines the general drought definition to be adopted. For example, the U.S. Weather Bureau defines drought as a

> lack of rainfall so great and long continued as to affect injuriously the plant and animal life of a place and to deplete water supplies both for domestic purposes and for the operation of power plants, especially in those regions where rainfall is normally sufficient for such purposes [*Havens*, 1954].

Similarly, a typical textbook definition of hydrologic drought is given by *Linsley et al.* [1975] as 'a period during which streamflows are inadequate to supply established uses under a given water-management system.' Agricultural droughts are usually described in terms of crop failure from decline in soil moisture, without any reference to streamflow. Therefore, it is apparent that drought is generally defined as a water shortage with reference to a specified need for water in a conceptual supply and demand relationship.

Clearly, the nature of the hydrologic cycle indicates that periods of low rainfall, low runoff, and low soil moisture should be intimately related. Precipitation is one of the inputs to a watershed system (which is composed of geologic and geographic components), and streamflow is one of the outputs; therefore, if one is interested in determining the cause of drought events, attention should be focused on precipitation drought (along with other aspects of climate and the watershed system); if one is interested in determining the effects and impacts of drought events, attention should be focused on streamflow drought and agricultural drought. With these distinctions, drought causes become the province of the meteorologist while drought effects become the province of the hydrologist and agriculturalist. The problem of estimating the frequency of drought occurrence falls to both the meteorologist and the hydrologist; neither has had much success in this area to date.

Because social scientists, politicians, and economists are concerned only with the effects and impacts of drought events, their primary interest should be with streamflow, water storage, and soil moisture deficits. The operators of supply management and demand management mechanisms (e.g., reservoir storage allocation, importation, pricing, conservation, reclamation) focus attention on the outputs rather than the inputs of the hydrologic cycle and hence benefit from advancement in the understanding of droughts on the part of the hydrologist. Thus a drought event manifests itself in the input, watershed system, and output components of the hydrologic cycle. This suggests two approaches to drought analysis: (1) analyze the stochastic structure of each of the individual system components, (2) analyze the interaction between the three components as one hydrologic system.

The first approach has been more prevalent in practice for the reasons stated earlier. Examples of the second approach include the use of rainfall-runoff simulation models [*Crawford and Linsley*, 1966; *Schermerhorn and Kuehl*, 1968], the use of precipitation drought frequency and a lumped geomorphic index to estimate runoff drought frequency [*Huff and Changnon, Jr.*, 1964], and the use of multiple regression techniques to estimate low streamflows from climatic, geologic, and geographic indices [*Thomas and Benson*, 1970; *Paulson*, 1978]. Each of these methodologies makes use of the fact that precipitation records generally cover a longer period of time and are more complete than streamflow records for the same region. The two approaches to drought analysis are clearly interrelated. One must understand the nature of each individual drought component before they can be combined in a complete systems analysis. The results of these two stages of drought study should be combined so that a method of comprehensive drought analysis has been achieved. Thus even though the drought analyst may elect to focus attention on only one of the drought components, it is necessary that he be aware of the ways in which that component affects and is affected by the other forms of drought manifestation.

THE AVERAGING PERIOD

After selecting the nature of the water deficit to be studied, the drought analyst must decide which unit of time or duration will be used as the averaging period for the meteorologic or hydrologic variables under consideration. Because the important variables are essentially continuous in nature (with the exception of precipitation), it is necessary to discretize the continuous time series by employing a specified averaging period which renders the data suitable for analysis. Sample averaging periods may vary from 1 hour or less, for the analysis of flood events, to one decade or more, for the analysis of large-scale climatic changes. For the study of drought events, averaging periods vary from months to seasons to years.

For example, droughts 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 1 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. Whereas drought events are drawn from a continuous time series of monthly, seasonal, or yearly data, only one low-flow event is selected from an annual period of data (or, in the case of a partial series analysis, only those events exceeding a specified base value). Examples of low flows which exhibit this sampling procedure are the annual minimum daily stream flow and the 7-day, 10-yr low flow.

The selection of the averaging period 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 averaging period results in a larger number of drought events while a longer averaging period 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 streamflow and thus separate the single drought year into several month-based drought events.

To demonstrate the effect of the length of the time series averaging period on the sample size of drought events, Table 1 contains the number of drought events in three streamflow records from the Central Valley region of California which resulted from the use of monthly, seasonal (3 months), and yearly averaging periods. On the average, the use of annual streamflow data yields about one sixth 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 drought events is set at 1 year, obtaining such an adequate sample size presents a significant problem. For instance, a typical 40-yr streamflow record in California's Central Valley contains only 10 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 averaging period is the degree of correlation between successive drought events. In general, a shorter averaging period tends to result in greater serial correlation in the

TABLE 1. Effect of Averaging Period on Drought Sample Size (SS) and Series Serial Correlation (SC) for Streamflow Records in the Central Valley of California

Stream	Averaging Period					
	1 month		3 months		1 year	
	SS	*SC*	*SS*	*SC*	*SS*	*SC*
Kings River	63	0.71	25	0.04	12	−0.07
Sacramento River	57	0.53	19	0.17	8	−0.02
Woods Creek	72	0.48	23	0.04	12	−0.07

All streams selected have no upstream diversion or regulated storages.

time series; thus monthly drought events usually exhibit more serial correlation than yearly ones. The use of longer time periods apparently smooths out short-term effects of natural carryover storage and climatic stability which may have a substantial impact on droughts based on a shorter time period. The impact of averaging period on serial correlation in hydrologic records is shown for Central Valley streams 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 [*Gumbel*, 1958; *Stall and Neill*, 1961; *Matalas*, 1963; *Dalrymple*, 1960; *Whipple*, 1966]. 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.

Hence the averaging period used to identify the basic time unit that describes a drought event has been shown to affect 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 averaging period (i.e., 1 year) results in a smaller sample size and smaller serial correlation. Although the selection of the averaging period 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 averaging period or another.

The Truncation Level

A necessary component of a complete drought definition is a specification of the method by which drought events will be abstracted from the remainder of the meteorologic or hydrologic time series. This component is referred to 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 most clearly seen when the statistical theory of runs is adopted for the analysis of the time series [*Yevjevich*, 1967]. The runs methodology is useful in analyzing a sequential time series of stochastic or deterministic variables and hence is well suited to the study of hydrologic and meteorologic events. The fundamental parameters of the runs of an annual hydrologic series are shown in Figure 1. The truncation value X_0 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_0), the run intensity (average deviation from X_0), and the run length (distance or time between successive crosses of X_0). In more common drought terminology, run sum is termed severity, run intensity is termed magnitude, and run length is termed duration. These three parameters are the fundamental descriptors of drought events. They are related by the expression $S_L = M_L \cdot D_L$.

In practice, the selection of X_0 is not arbitrary but rather is a function of the type of water deficit being studied. For the study of multiyear hydrologic droughts, X_0 may be selected as the mean annual runoff of a watershed; for the study of seasonal agricultural droughts, X_0 may be selected as the mean soil moisture present during the prime growing season. Theoretically, X_0 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

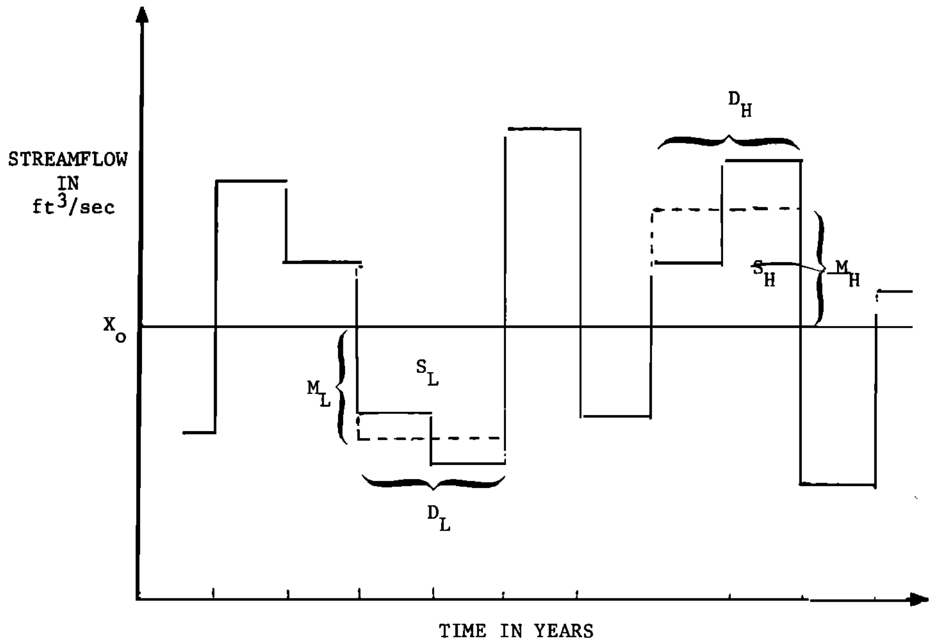

Fig. 1. Fundamental parameters of the runs of a series.

series, it may be convenient to choose a truncation level such as

$$X_0 = X_m - e \cdot S_D$$

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.' 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. The importance of skewness in low-flow frequency analysis has been discussed by *Matalas* [1963].

By combining the notion of the truncation level with the notion of the averaging period 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 averaging period. These are shown schematically in Figure 2. The conventional definitions are as follows: 'flood' is above X_0 with short averaging period, 'low flow' is below X_0 with short averaging period, 'high flow' is above X_0 with long averaging period, and 'drought' is below X_0 with long averaging period. 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. Utilizing 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 analyses of these two types of events.

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

Hence certain advantages of standardization may be realized 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 a historical series, however, one must be cautious of grossly unrepresentative events included in the sample, particularly if the sample size is small. For example, the worst drought in a 30-yr 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 favor 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.

THE REGIONALIZATION APPROACH

In arriving at a concise drought definition for use in an analysis, it is necessary to stipulate the approach to regionalization that is being employed. There are three fundamental choices available:

(1) Do not regionalize the analysis. Restrict attention to the

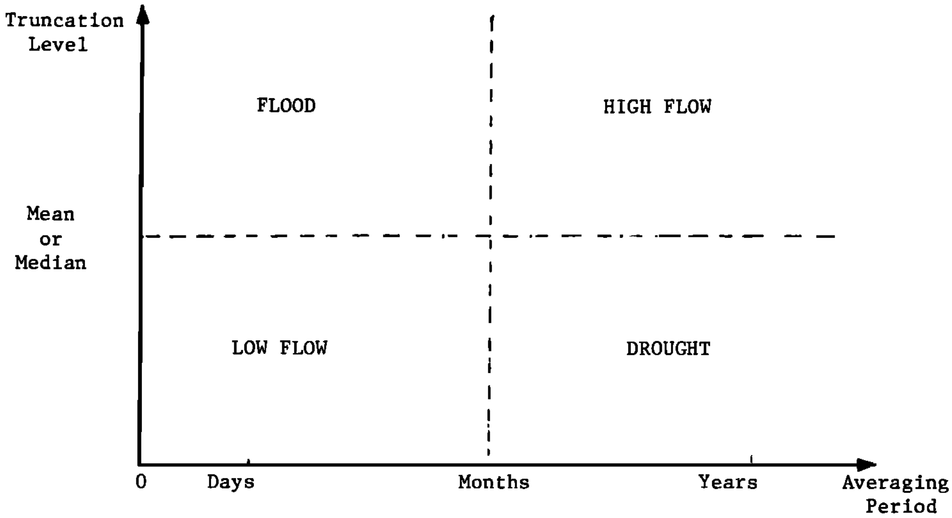

Fig. 2. Classification of hydrologic events.

drought record of only one stream gage, rain gage, or soil moisture gage.

(2) Define a region according to similar climatic input, similar geomorphic characteristics, and geographic proximity.

(3) Define a region according to similar statistics of the hydrologic or meteorologic records, regardless of the location of these records.

The first regionalization option, actually the no-regionalization option, is not generally feasible in application to drought analyses for two reasons. First, droughts are inherently regional in nature, and thus their areal extent is an important characteristic to be considered. Second, the small sample size of drought events is often a limiting factor in their analysis, and regionalization provides a means for increasing this sample size.

In selecting between the remaining two regionalization alternatives, it is useful to recall the input-system-output model of drought classification discussed earlier. 'Input' refers to precipitation and meteorologic droughts: a regionalization approach for the study of these events should involve grouping records according to homogeneity of climate and weather patterns. 'System' refers to the watershed itself and agricultural or soil moisture droughts; a regionalization approach for the study of these events should involve grouping records according to homogeneity of geology and geography. 'Output' refers to streamflow and hydrologic droughts; one regionalization approach for the study of these events involves grouping records according to homogeneity of climate and geomorphology. This is based upon the assumption that if input and system components are homogeneous, the output component should be homogeneous as well. These three regionalization approaches are straightforward in theory but often difficult to apply in practice [*Langbein*, 1947: *Dalrymple*, 1960].

The third alternative in regionalization is perhaps more correctly termed standardization. It would allow drought records to be grouped solely on the basis of certain selected statistics, without stipulating that the records be associated with coterminous areas. This approach is most applicable to an analysis of streamflow drought, since the regionalization (or standardization) procedure would be based only on characteristics of the hydrologic series and not on factors of climate and geomorphology, which more directly influence precipitation and soil moisture drought. This method of grouping records may yield more accurate results than conventional regionalization methods, although further study is required to determine the optimal record statistics to be used as the standardizing parameters. The problem with the standardization approach is that while it aids in alleviating problems associated with small drought sample sizes, it fails to account for the areal extent of drought events. In this respect, standardization is more appropriately used in the study of floods and low flows rather than droughts. Nonetheless, if standardization is utilized in lieu of a conventional regionalization approach for drought analysis, then some method must be developed to incorporate the characteristic of areal extent in the analysis.

When precipitation, soil moisture, and streamflow drought are to be studied as a complete system, or when one type of drought is to be inferred or estimated from the others [e.g., *Huff and Changnon, Jr.*, 1964; *Thomas and Benson*, 1970], the homogeneous regions corresponding to the three classes of drought events should overlap as much as possible. This allows for legitimate comparison among droughts occurring in the three principal components of the hydrologic cycle. Thus, in this case, regionalization in terms of homogeneity of climate and geomorphology, in addition to geographical proximity, is recommended rather than the standardization approach.

Discussion

In order to investigate methods of performing frequency analysis of drought events, the following steps are required, in order to define and select the type of drought event to be studied.

First, attention should be focused on droughts as they most directly affect man's activities. This means being concerned with water supply, water quality, hydroelectric power generation, water-based recreation, and irrigation. All of these classes of water utilization are directly affected by streamflow, either in itself or as it contributes to reservoir storage. Emphasis is on the effects and impacts rather than the causes of drought events. Meteorologic and agricultural drought would be considered only insofar as they affect hydrologic drought through the processes of the hydrologic cycle.

Next, it is necessary to select the averaging period used to define the drought events. Proper operation and management of water resource projects is able to mitigate most water deficiencies occurring over short time periods. Therefore, streamflow drought lasting at least 1 year and an annual averaging period should be selected. Another important reason for choosing this averaging period is that less attention has been given to the frequency analysis of these extreme extended drought events than to other hydrologic phenomena [*Whipple*, 1966]. Selecting this long averaging period means something will have to be done to increase the drought sample size, but serial correlation is not expected to be detrimental to the frequency analysis.

Choosing mean annual runoff as the truncation level has certain advantages to this kind of analysis. First, it standardizes the severities of high and drought flows, and severity is perhaps the most important drought characteristic affecting water resources projects. Second, the mean attributes more significance to the extremes of the drought distribution, and it is these extreme events with which the frequency analysis is most concerned. Thus average annual streamflow should be selected as the truncation level.

Because the long averaging period selected renders use of a single streamflow record infeasible, from the standpoint of drought sample size, some method of regionalization must be employed. The type of regionalization depends upon the particular method of frequency analysis used. A multiple-regression approach can be utilized to estimate parameters of multiyear drought frequency from climatic and geomorphic characteristics [*Paulson*, 1978]. In this study, the conventional method of regionalization, which combines records of adjacent streams, was used in order to preserve climatic and geomorphic homogeneity. On the other hand, any analysis of the stochastic characteristics of drought severity, magnitude, and duration may benefit from a standardization approach rather than regionalization. Thus both methods of regionalizing the analysis appear to be applicable to drought analysis.

Conclusion

The problem of developing a unique definition of the drought event has plagued the field of water resources for many years, Unfortunately, the variety of existing drought concepts makes the attainment of such a unique definition virtually impossible, and thus the drought analyst is required at the outset of a project to clearly specify the particular type of drought to be studied. This paper has suggested a systematic approach to drought definition, incorporating the use of the theory of runs, which requires the analyst to select the nature of the water deficit to be studied, the averaging period used to discretize the raw data, the truncation level used to distinguish droughts from other events, and the regionalization approach. A number of possible alternatives relating to each of these four decisions have been discussed, including precipitation, soil moisture, and streamflow water deficits; monthly, seasonal, and annual averaging periods; mean and median truncation levels; conventional geographic regionalization; and statistical standardization. The implications of selecting particular components of the drought definition have been presented, as well as a brief description of the application of this drought definition procedure to multiyear hydrologic droughts.

It has been shown that these aspects of drought definition affect sample size; serial correlation; drought severity, magnitude, and duration; and the degree to which areal extent is considered in the analysis.

This systematic approach for developing a clear and concise drought definition, including an awareness of the advantages and disadvantages of a particular definition to a proposed analysis, is recommended for use by meteorologists and hydrologists as a tool for focusing attention on the precise drought concept with which they are concerned.

NOTATION

D_H duration of high flow.
D_L duration of low flow.
e elective scaling factor.
M_H magnitude of high flow.
M_L magnitude of low flow.
S_H severity of high flow.
S_L severity of low flow.
SC serial correlation.
SS sample size.
S_D standard deviation of a time series.
X value of a time series.
X_m mean of a time series.
X_0 truncation level of a time series.

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