

AN OBJECTIVE APPROACH TO DEFINITIONS
AND INVESTIGATIONS OF CONTINENTAL
HYDROLOGIC DROUGHTS

by

Vujica Yevjevich

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The support by the U.S. National Science Foundation under Grant No. GK-169 in the research leading to this hydrology paper is gratefully acknowledged. This paper outlines a position on the problems of large continental droughts, based on the results of several studies carried out in the past and at present under the National Science Foundation support.

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ABSTRACT

The major objective of the paper is to emphasize the needs for a systematic research into many facets of large continental droughts, and to outline methods for an objective definition of these droughts. Various ambiguities present difficulties in defining hydrologic droughts. Concepts are advanced to allow the objective definition of these droughts. Elective factors are singled out as the basis of definition: The phenomenon determining drought, the variable which properly describes this phenomenon, the moisture level at which a drought starts, and the area to which a drought is related. The runs as statistical properties of time and space distribution of water deficits are recommended as parameters for drought definition.

Three types of runs represent attractive parameters for drought definitions: (1) run-length of negative deviations of a time series (duration of drought); (2) run-sum of negative deviations between a downcross and an upcross of a time series (severity of a drought); and (3) area-run as the deficit of water over a time duration (run-length) and area of drought. For known properties of hydrologic time series and dependence between time series, the runs can be determined either analytically for simple cases or by the data generation method (Monte Carlo method) for more complex cases. Examples for these two methods in determining the properties of runs are given for the independent standard normal variable and the independent standard log-normal variable with two different skewness coefficients.

A review is made of results obtained at Colorado State University in the last 4 to 5 years on the properties of precipitation, effective precipitation and runoff which affect the description of droughts and explain the outlook for drought prediction. Briefly, the outlook for prediction of large continental droughts and the potential causal factors for explanation of large continental droughts are discussed. An approach is proposed for prediction of large continental droughts by the search for interrelationship of oceanic synoptic situation and continental precipitation. Some measures are explored which offer a promise for combating large droughts.

AN OBJECTIVE APPROACH TO DEFINITIONS AND INVESTIGATIONS
OF CONTINENTAL HYDROLOGIC DROUGHTS*

by Vujica Yevjevich**

CHAPTER I

CONTINENTAL HYDROLOGIC DROUGHTS

1. Various concepts of drought. One of the first steps in the investigation of any problem is the definition of the problem itself; herein lies one of the principal obstacles to the investigation of droughts, for there is a wide diversity in the ways in which different fields of study view droughts.

The geophysicist's view of drought may be climatological, general meteorological, hydrological, limnological, glaciological, or concerned with aspects of soil physics.

The engineer views drought as a set of variables affecting rainfall, runoff, and water storage in its many forms.

The economist views drought from an entirely different point of view, that of the areas of human activity affected. In his eyes, there are agricultural droughts, water supply droughts, and droughts involving fish, wildlife, and range management, to name only a few.

The agriculturist has another point of view, closely tied to the water needs of various crops. A drought for tomatoes, for instance, may not be a drought in the eyes of the grower of potatoes. For each, the concept of drought changes during the growing season, mainly by climatic variations, but also according to soil conditions, growth state, and the ways in which the crops are cultivated.

Every water user has its own conception of drought, and that conception changes with the user's conditions of operation.

One objective of this paper is a search for basic but objective definitions of hydrologic droughts. From this point, one can proceed to a second objective, an analysis of the types of investigations that should be made of droughts.

Initially, the droughts can be referred to as a point drought, the small area drought, and the large continental drought. The latter will be mostly discussed in this paper.

2. Needs for investigation of droughts. Of all the main problems of hydrometeorology and hydrology, the properties of severe continental droughts are likely to be the least known. When they are computed

as the water deficiency in areal extension and time duration for any given probability of occurrence, the figures are usually of a very low accuracy. In studying various reports on the drought of the 1930's in the Upper Missouri River, one can find estimates of return period of that drought ranging from 75 to 3000 years.

Here is a strong indication that large continental droughts are not well understood, described, or explained; their properties are not known with sufficient accuracy to allow predictions of their occurrence, duration, or intensity with any real degree of reliability.

This is not due to lack of existing information from past observations of precipitation, evaporation, runoff, or water storage; rather, it is due to the way in which this existing information has been interpreted. It has not been generalized with reference to the basic characteristics of large continental droughts, particularly with the intent of predicting the probabilities of recurrence.

Several factors have made such an interpretation of data difficult, if not impossible:

First, a tremendous amount of data had to be collected, assembled, stored and processed, which was not feasible, practical or economical in the pre-computer age.

Second, the objective definitions of drought were and are still lacking, such that each researcher would obtain the same results on droughts from the same basic data.

Third, the scientific methodology of investigation of large area droughts is not yet well developed.

Fourth, the importance of drought investigation is not fully recognized, and necessary funds for that purpose have not been available.

Fifth, potential research centers and competent researchers have been mainly concerned with other problems of hydrometeorology and hydrology.

As in many other areas, the general public reacts favorably to requests for investigations of floods and droughts only when an important area is

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hit. The drought of the northeastern United States during the last six years should spur the study of continental droughts on a large scale.

Many questions about droughts require answers: What would be the probability and consequences of a severe and prolonged drought in the mid-western United States? How could these consequences be mitigated or even avoided? The same questions could be raised about many areas of the nation, notably the densely populated Southern California area and the megalopolis which extends from Boston to Washington, D. C., as well as for similar areas in other parts of the United States and of the world.

3. Basic types of investigation of continental droughts. To obtain the needed information about continental droughts, the following basic investigations are needed:

(a) To describe droughts, mainly by setting up standards of water deficiency in areal extension over time duration, dependent on water demand factors within the area to which the standards are to be applied; thus one could say, "If these conditions of water deficiency persist over a certain length of time in this particular area, it has a drought."

(b) To determine and explain the physical causal factors of large continental droughts, and

(c) To develop methodology for the prediction of the initiation, duration, severity, and recurrence of large droughts.

The probability of a given type of drought can be obtained only from existing data on variables related to well defined droughts. It can be determined by a proper statistical analysis of all available data. When the drought is well defined, and the data properly assembled, three methods of investigation for the description and determination of the probability of droughts can be used:

(1) Empirical method, or deriving the information on drought probabilities of the order of a return period which is smaller or equal to the period of observation by using the length of observed time series.

(2) Data generation method, or deriving, in an approximate way, of droughts of large return periods which are equal to or much greater than the period of observation, by generating in the proper way large samples of data (Monte Carlo method).

(3) Analytical method, or deriving the return period of any drought by generalizing the properties of the available time series and areal relationship of various variables affecting the droughts, and thus obtaining overall drought characteristics and their probabilities.

The main objectives of these investigations are:

(1) To ascertain the return periods of particularly severe droughts, and to assess their economic and general impact on a large continental region;

(2) To determine whether the risks involved, and the probabilities of those droughts warrant any particular measure and investment for combating their consequences; and

(3) Whether an insurance approach, or government support should be the principal means of alleviating the consequences and damage of these large continental droughts.

The first objective can be attained by a well-developed methodology of investigation. Explanation of large continental droughts is possible through studies of synoptic situations of oceans and atmosphere preceding the drought, throughout its duration and termination. By this means one can ascertain whether there are phenomena in atmosphere and oceans particularly those which precede droughts by a sufficient lag of time and which cause their persistence. At present, little is known of the factors which determine the onset, duration, and areal extent of large continental droughts.

The second purpose requires an extensive engineering and economic study in ascertaining the risks, potential damage, measures and structures needed as well as the uncertainties in their performance and efficiencies.

The third purpose can be accomplished by an appropriate national or regional planning of water resource developments with a special emphasis on a policy to combat drought.

Basic economic, social and political studies are needed to answer which alternative would be best suited for the problems of combating large continental droughts.

The prediction of three characteristics: initiation, duration and severity of forthcoming large continental droughts is a very difficult and seems sometime an impossible task. It is a known fact that the series of annual precipitation at a gaging station is very close to the series of independent variables. It is also an important factor that the simultaneous values of annual precipitation at various adjacent gaging stations are dependent among themselves up to distances of about 800-1200 miles. This distance of practical dependence is a function of both the regional precipitation patterns and the orographic obstacles to the moving air masses. With these general characteristics of precipitation in mind, one is logically tempted to raise the question of the outlook for the prediction of large and prolonged continental droughts.

It is an attractive approach to assume that only the various synoptic conditions of extended ocean areas are factors which affect the occurrence and create time persistence of large continental droughts. The clue for the future prediction of those droughts must necessarily lie primarily with the investigation of ocean synoptic conditions and with the study of air-sea interactions, giving the preference to the former. Atmospheric circulation does not seem to predetermine substantially the occurrence of the prolonged and severe continental droughts. The simple fact is that the non-conservative properties of air as a fluid, with a large impact of turbulence and vorticities at various frequencies as random phenomena in the atmospheric circulation, make the time dependence in series of atmospheric phenomena a relatively rapidly decaying property.

The time lag between a given synoptic situation of large areas of oceanic water and the corresponding synoptic situation over a continental area seems to be the main expectation for the future prediction of large droughts. Both synoptic situations must be properly defined from the drought point of

view before their relationship is attempted. The time lag factors for these two synoptic phenomena are not yet well understood, and the quantitative values of these lag factors are less well known.

Regrettably, the ocean synoptic situations have been observed and studied only for the following basic objectives: (a) for navigation, (b) for fishing, (c) for weather prediction and (d) for the exploitation of ocean natural resources. Oceans have not been systematically investigated as the water supply sources for large continental areas. Who can tell at this time where the millions of acre-feet of precipitated water above the Columbia River Basin come from? Who can tell how and from where the millions of acre-feet of evaporated water from an ocean patch or a sea are replaced, when there are substantial differences in evaporation rates over adjacent ocean areas? Who can tell at this moment whether and how the synoptic situation of the water surface and the upper water layer (heat storage, currents, etc.) of the Gulf of Mexico and the synoptic situation of moisture deposition over Texas are related? Similar questions may also be raised.

The prediction of characteristics of large continental droughts is of paramount economic im-

portance. The policy of operating storage reservoirs, the transfer of water, the economic use of the available water supply, and similar policies all could be implemented sufficiently in advance to minimize the drought damage and the other drought consequences.

Present-day electrical management practices are to transfer energy from areas of surplus to areas of deficiency when proper interconnections between regions are available. The same concept might be used for the conservation of water, under the following conditions:

- (1) That the recurrence intervals of continental droughts warrant the consideration of this alternative;
- (2) That the drought characteristics can be ascertained sufficiently in advance; and
- (3) That conveyance structures and equipment for water transfer can be economically installed. This last alternative in combating droughts in important industrial complexes and large population centers warrants a serious investigation. Desalination plants are a solution for combating droughts along coastal areas.

CHAPTER II

OBJECTIVE DEFINITIONS OF HYDROLOGIC DROUGHTS

1. Meaning of the term "objective definition." The term "objective definition" implies that the criteria, methodology, and techniques in the definition of droughts are set up in such a way that various people, interpreting them in the same way, will come to the same results for large droughts from the same basic data. Any elective factor in drought definitions must be recognized, and its selection made according to a particular definition of the drought.

2. Hydrologic droughts. The term hydrologic droughts is defined here as the deficiency in water supply on the earth's surface, or the deficiency in precipitation, effective precipitation, runoff or in accumulated water in various storage capacities. Basically, a hydrologic drought means a deficit of water supply in time, in area, or both. Any hydrologic drought involves these factors:

(a) Duration; (b) Areal extension; (c) Severity (intensity); (d) Probability of recurrence; and (e) Initiation (or termination) - which means its location in the absolute time.

3. Phenomena and variables of drought definitions. For an objective analysis of droughts the main phenomena which are taken into account are:

- (a) Precipitation at ground level;
- (b) Evaporation from the ground, from bodies of water, through plants, etc;
- (c) Effective precipitation in the form of precipitation minus evaporation;
- (d) Runoff; and
- (e) Water stored in various natural or artificial storage spaces of all kinds.

Along the water cycle from the precipitation reaching the ground to water leaving an area, all the above phenomena may be relevant for an objective definition of droughts. Therefore, the first selection one has to make is the phenomenon or phenomena which are basis for the definition of droughts. Once the phenomenon is selected, the variable or variables which describe the phenomenon must be determined, such as whether to use a point measurement or a total area value, whether intensities (or discharges) in the form of continuous series are used or discrete values in the form of daily, monthly, annual, or any other time interval values, or whether levels, stored water or similar variables are selected.

The selection of drought definition phenomenon or phenomena, and the variable or variables which describe them, are the first steps to undertake in any objective definition of droughts.

4. Basic concepts for objective definitions of droughts. The runs, as statistical properties of sequences, both in time and area, represent, to the writer's view, the best basic concept for an objective definition of droughts. The runs of the sequence of a

stochastic variable (or a combination of stochastic and deterministic components making a composite sequence) may be defined in various ways. Figure 1 represents a series of a variable x . By selecting an

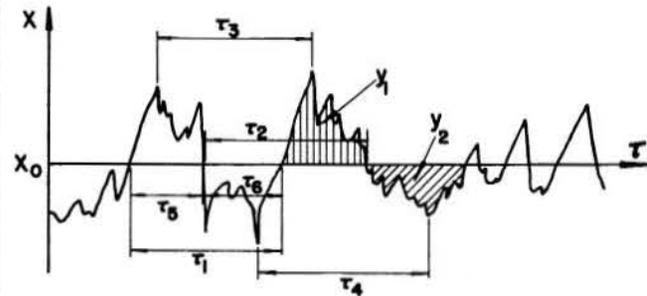


Fig. 1 For a given sequence $x(\tau)$ and the selected base value, x_0 , the concepts of runs which may be used for practical objectives of series analysis are: τ_1 - distance between upcrosses; τ_2 - distance between downcrosses; τ_3 - distance between successive peaks; τ_4 - distance between successive troughs; τ_5 - distance between the successive upcross and downcross; τ_6 - distance between the successive downcross and upcross; y_1 - sum of positive deviations between the successive upcross and downcross; and y_2 - sum of negative deviations between the successive downcross and upcross.

arbitrary value x_0 the series is cut at many places, and the relationship of the constant value x_0 to all other values of x serves as the basis for various definitions of runs. However, the parameter x_0 does not need to be a constant and may be conceived as a deterministic function, a stochastic variable or a combination thereof. For the sake of simplicity, this value x_0 is assumed in all further discussions to be an arbitrary constant which must be selected before the droughts are analyzed.

Various concepts of runs are used in literature, and some of them are as follows (see fig. 1):

1. τ_1 - distance between upcrosses,
2. τ_2 - distance between downcrosses,
3. τ_3 - distance between successive peaks,
4. τ_4 - distance between successive troughs,
5. τ_5 - distance between the successive upcross and downcross,
6. τ_6 - distance between the successive downcross and upcross,
7. y_1 - sum of positive deviations, between the successive upcross and downcross, and

8. y_2 - sum of negative deviations between the successive downcross and up-cross.

Similar definitions of other runs may also be given.

For the purposes of drought definitions, τ_5 , τ_6 , y_1 , and y_2 seem to best suit the practical needs in measuring water deficits and their durations.

5. Time-runs as elements of drought definitions. For the given series of x-variable and a selected value x_0 , the two types of runs defined above: (1) distances between successive upcrosses and downcrosses, or vice-versa; and (2) sums of all deviations between the upcrosses and downcrosses, or vice-versa, represent, in the writer's view, the most attractive way of describing the droughts. The distances are the run-length of negative deviations in the case of droughts, in the first case, and represent the duration of a drought. The sums of deviations are the run-sum of negative deviations for a given run-length in the case of droughts, and indicate the deficiency of water supply or the severity of drought. Figure 2 represents schematically these two types of runs, designated by n and S_n , respectively, for both a continuous and a discrete time series. The ratio

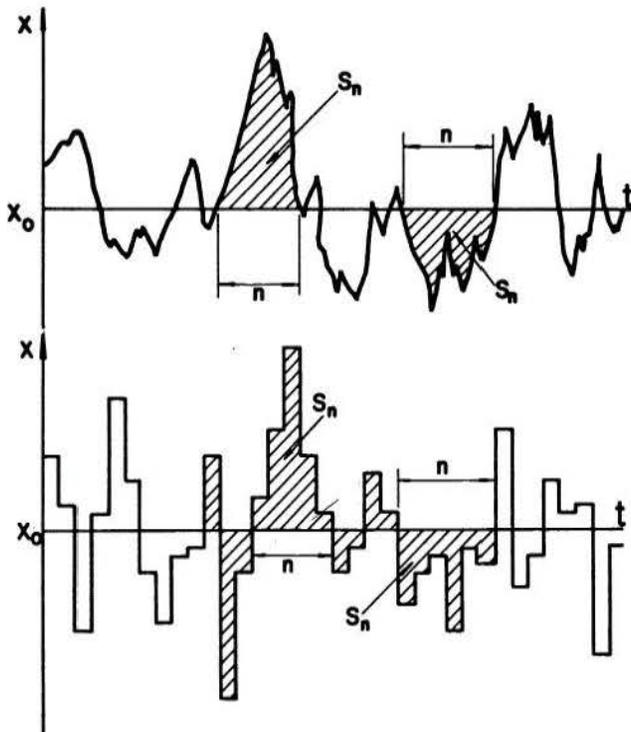


Fig. 2 The run-length of negative deviations as the time duration of a drought (n), and the run-sum of negative deviations as the water deficiency in a drought (S_n), for a given base value x_0 , which defines the onset and the termination of droughts, for both a continuous time series (upper graph) and a discrete time series (lower graph).

of the run-sum to the run-length represents the average deficiency of water supply, and is also a property of runs for the definition of drought characteristics. The runs in the form of the sum, the length, and their ratio refer to the time series of the

basic variable of the drought definition. In the case of precipitation or effective precipitation (precipitation minus evaporation), the time-runs refer either to the point values or to the average or totals over an area. For runoff or accumulated water in various storage capacities, the time-runs refer to the totals or averages of overall conditions of drought over the given river basin above the gaging station, or to the total volume of the body of water stored.

6. Area-runs as the basis for definitions of continental droughts. For precipitation, effective precipitation, runoff from small river basins, stored water in various capacities over a large continental area, the total deficit of water supply in that area below a defined x_0 -value of the basic variable, and for given time duration represents the area-run of negative deviations from x_0 . Two concepts are feasible:

(1) The duration of individual time-runs is the same for each individual station, river basin runoff, or storage condition over individual storage capacities. This duration is a changing parameter (say, one-year, two-year, . . . , n-year drought duration), so that area-runs are computed for each duration. (2) Duration varies from station to station, or from river basin to river basin, or from storage to storage capacity. In this latter case, only time-lengths of negative deviations are taken into account, and these lengths may vary significantly among stations of a region covered by a continental drought.

Regardless whether one or the other of the two above area-run definitions is used, these are time-area runs of water deficiency for a given parameter value x_0 . The water deficiency is represented in fig. 3, and is obtained over an area by using the negative run-sum S_n at each individual station.

The total water deficit is obtained from these isolines of negative run-sums for all values below the isoline zero.

The area of drought coverage may also be an important parameter to be selected. The area covered by a drought usually increases with both the severity and the duration of a continental drought. Therefore, two options are available: (1) Area is an elective parameter (say, one is interested in the coverage by drought of a state region, or several states, but not beyond the periphery of that area); and (2) Area is a stochastic variable, changeable with every drought. A selection between these two alternatives must be made before an objective definition of continental drought is obtained. In the first case, the stress is on the area; in the second case, the stress is on the central station and drought coverage associated with what is happening around that central station.

7. Advantage of using runs in drought definitions. The main advantage of using runs as the elements of drought definitions is the possibility of determining their properties (distribution, time dependence, and similar) analytically or by data generation method once the characteristics of basic variable, both as its time series at any station and the dependence from station to station, are known. By describing properly the hydrologic processes in time at all stations of a region, and the dependence between stations, one should be able to use either the analytical or data generation method to derive the properties of various runs. It should be possible, therefore, to determine the probability of a given run-sum of a given run-length of monthly values at a precipitation station, once that series is available and properly described

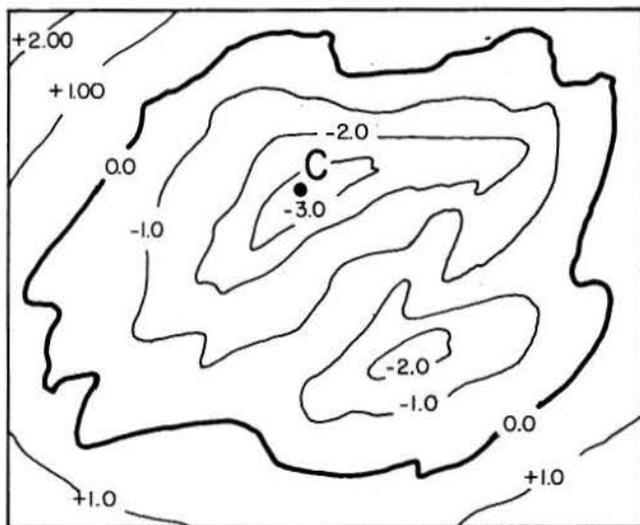


Fig. 3 Definition of the negative time-area runs of water deficiency represented as isolines of equal run-sum values (S_n) of individual stations, given in the upper graph, with its central station of greatest deficiency, and its run-sum (S_n) and run-length (n), given in the lower graph.

mathematically. Similarly, an area-run of water deficiency can be described for its recurrence properties if time series of all stations and dependences between series are described by the proper mathematical models.

In case the analytical approach becomes unfeasible or very complex, the data generation method (Monte Carlo method) is an experimental approach always available to obtain properties of runs with a desired accuracy. This accuracy may be improved in two ways: (a) by generating more random numbers and testing their properties; and (b) by generating time series and dependence between them in such a manner that they do not deviate significantly from the properties of observed series and dependences.

8. Elective parameters. In defining continental droughts by area-runs of the type shown in fig. 3, the following factors should be first defined:

- (1) Phenomena underlying the definition of the drought (precipitation, runoff, or others);
- (2) Variables of the drought (rainfall intensity, river discharge, monthly precipitation, monthly runoff, annual precipitation, annual runoff, stored water, and similar);
- (3) The basic reference parameter, x_0 , for variables of time-run determinations;

(4) A central station (fig. 3, C) for which the length of drought time-runs (n) is determined, and for which the dependences of variables of adjacent stations are computed;

(5) Selection of n or several values of n as durations of runs at all stations, if the approach of equal durations is used.

(6) Selection of area (A) if it is a parameter, or when the area is a parameter.

Only when all decisions concerning the above selections have been made, is it possible to uniquely define droughts by area-runs.

The selection of x_0 , the base value of the variable, is the crucial decision. Figure 4 demonstrates how the run-length and run-sum substantially change when x_0 changes. One may be tempted to use

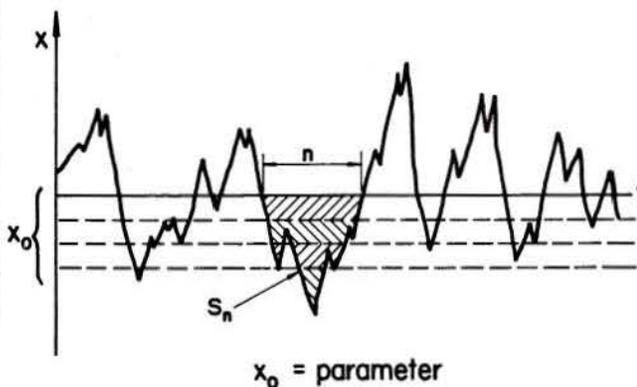


Fig. 4 The effect of selective parameter x_0 on the run-length (n) and run-sum (S_n).

the mean of x as the x_0 -value, and this approach has several advantages. Median of x may be also used in some cases. However,

$$x_0 = \mu + \alpha \sigma \quad (1)$$

with \bar{x} = the estimate of the mean μ and s = the estimate of the standard deviation σ of x , and α = an elective value which represents well the various aspect of the base parameter. The parameter α determines how much x_0 deviates from the mean in terms of standard deviation. One may select $\alpha = -0.2$, or $x_0 = \bar{x} - 0.2s$, and it represents the level of water supply when drought begins. The selection of x_0 may be changed with time as the demand for water and water use changes in a region with time.

The selection of the central station of a drought is also an important decision. This center usually shifts from year to year as a protracted continental drought goes on. When the drought is over, the station with the largest negative run-sum for given duration (run-length) may be considered as the drought's severest point, though the center of the body described by isolines in fig. 3 may be quite removed from the station of the largest run-sum.

9. Example of analytical determination of properties of runs. For the time-runs in the form of

run-length (n), it is well known that for a discrete time series one needs only to obtain the probabilities of x values greater than x_0 as p , and for the lower values than x_0 as $q = 1 - p$, and the properties of the run-length may be obtained regardless of the underlying distribution of the variable x , provided it is an independent variable [1]. Distribution of run-length of size n , $n = 1, 2, \dots$, is given for an infinite population by

$$f(n) = qp^{n-1} \quad (2)$$

when $f(n)$ is the probability of run-length of size n , with the mean

$$E(n) = 1/q \quad (3)$$

and the variance

$$\text{var } n = p/q^2 \quad (4)$$

For a sample of size N , the values of p and q must be estimated by the frequencies $p_e = N_1/N$ and $q_e = N_2/N$, with N_1 number of x -values above x_0 , and $N_2 = N - N_1$ the number of x -values below x_0 (see fig. 5). In this case,

$$f(n) = \frac{N^2}{N_1 N_2} \left(\frac{N_1}{N}\right)^n \left(\frac{N_2}{N}\right)^2 = \frac{N_2}{N} \left(\frac{N_1}{N}\right)^{n-1} \quad (5)$$

The inherent error in $f(n)$ is due to the limited sample size N .

For a time dependent variable x , the above equations (2) through (5) must be revised and expressed in function of various time dependence models.

The determination of properties of the run-sum S_n is more complex. Its distribution depends on the distribution of x . For an independent standard normal variable (0, 1, 0), --or mean zero, variance unity, and all autocorrelation coefficients ρ_k (with

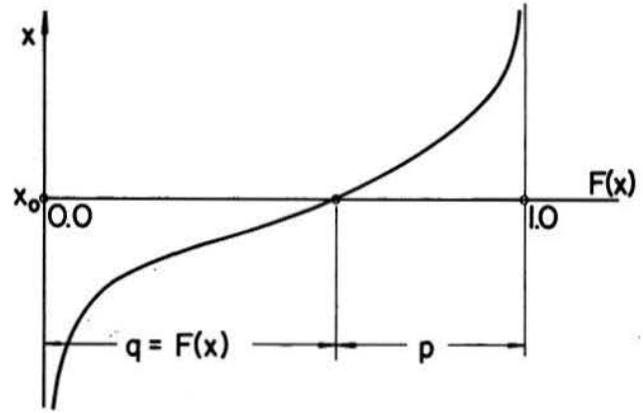


Fig. 5 To estimate by eq. (2) or eq. (5) the properties of run-length of discrete time series of a random independent variable of any distribution, the estimates of probabilities of x smaller than x_0 are necessary (p , and $q = 1 - p$).

$k > 0$) zeros -- the exact properties of run-sum are obtained by using their cumulants [2]. In the case of $x_0 = 0$ (mean of standardized variables), or $p = q = 1/2$, the mean, the variance, the third central moment, and the skewness coefficient of S_n are, respectively:

$$E(S_n) = 4(2\pi)^{-1/2} = 1.59576, \quad (6)$$

$$\text{var } S_n = 2.00, \quad (7)$$

$$E[S_n - ES_n]^3 = \frac{16}{\pi\sqrt{2\pi}} + \frac{8}{\sqrt{2\pi}} = 5.2232, \quad (8)$$

and

$$C_s(S_n) = E[S_n - ES_n]^3 / (\text{var } S_n)^{3/2} = 1.84668. \quad (9)$$

Table 1, taken from the reference [2], gives the exact properties of run-sum for the independent standard normal variable for various values of x_0 .

TABLE 1
EXACT PROPERTIES OF THE RUN-SUM FOR THE INDEPENDENT STANDARD NORMAL VARIABLE

x_0	q	$E[S_N]$	$\text{Var}[S_N]$	$C_s[S_N]$	$\rho[N, S_N]$
-1.00	0.15866	8.11547	59.38017	1.99134	0.966
-0.75	0.22664	5.02726	22.00020	1.97838	0.943
-0.50	0.30854	3.27079	8.97299	1.95301	0.908
-0.40	0.34458	2.79145	6.44255	1.93786	0.890
-0.30	0.38209	2.40055	4.69334	1.92055	0.871
-0.20	0.42074	2.07983	3.47846	1.89870	0.849
-0.10	0.46017	1.81524	2.61713	1.87411	0.824
-0.05	0.48016	1.70033	2.28238	1.86108	0.811
0.00	0.50000	1.59576	2.00000	1.84668	0.798
+0.05	0.51984	1.50002	1.75936	1.83102	0.784
+0.10	0.53983	1.41271	1.55222	1.81661	0.769
+0.20	0.57926	1.25921	1.22313	1.78457	0.739
+0.30	0.61791	1.12989	0.99102	1.73613	0.701
+0.40	0.65542	1.02034	0.79406	1.71753	0.672
+0.50	0.69146	0.92714	0.65353	1.68473	0.636
+0.75	0.77336	0.74826	0.42596	1.60652	0.546
+1.00	0.84134	0.62411	0.29823	1.49263	0.455

between $x = -1.00$ and $x = +1.00$ (upto one standard deviation plus or minus from the mean). With the moments known, the approximate distributions of S_n for the various values of x_0 may be obtained.

There is a high correlation between the run-length and the run-sum. For $x_0 = 0$

$$\rho(n, S_n) = 2(2\pi)^{-1/2} = 0.798 \approx 0.80 \quad (10)$$

and it increases with a decrease of x_0 (see Table 1).

The above results show that the analytical approach is feasible for simple cases, and that the exact properties of run-sum may be derived for various distributions (time dependent or time independent) of the basic variable x .

The data generation method was used to derive the properties of run-sum for the independent standard log-normal variables x , with the skewness coefficients values 1.00 and 2.00 [2]. Figure 6 gives the mean, the variance, and the skewness coefficient of run-sum as a function of q which in turn is related to x_0 . Figure 7 gives frequency and cumulative frequency distributions for the independent standard normal ($C_s = 0$) and the independent standard log-normal ($C_s = 1.00$ and $C_s = 2.00$) variables, obtained by the data generation method.

The above two examples of run-length and run-sum properties, determined either by the analytical method or by the data generation method, point out an important approach for obtaining the

characteristics of droughts. Once a time series is properly described mathematically, either by the distribution of x only, or by the distribution of x and the mathematical model of time dependence structure, the properties of runs for various parameters of x_0 may be determined. In complex cases of time series structure, only the data generation method is feasible. Therefore, from the statistical point of view, it is important to obtain the best estimates of statistical properties of the basic variable x , and this accomplished, the properties of time-runs may be obtained as the best estimates by the above two methods: the data generation method (in complex cases) and the analytical method (in simple cases).

10. Probability of area-runs. It is necessary to fulfill one remaining condition for the computation of recurrence of a given area-run over a region. The area must be specified, and its central point defined. Then the data generation method may be used to obtain long time series at the central point. The regional correlation pattern between the adjacent stations is then used to produce time series around the central station by covering a sufficient number of points over the selected region. In this complex relationship, the data generation method is expected to be the only feasible technique in creating long series so that rare droughts may occur in a sufficient number and their probabilities assessed with sufficient accuracy.

Similarly, assuming the central station selected, and its long time series generated, then the generation of series of adjacent stations, with the area of negative runs as a variable, would determine a joint distribution of area-runs and area extension of droughts.

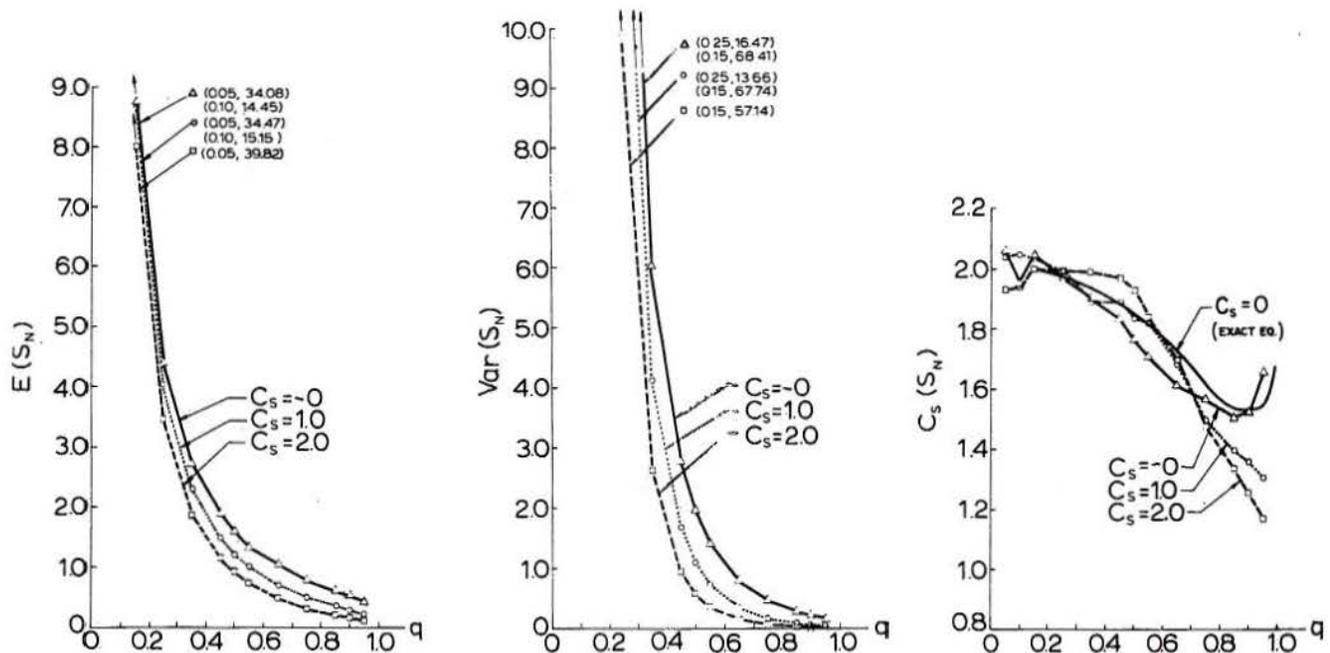


Fig. 6 Properties of run-sum for the independent standard normal variable ($C_s = 0$) and the independent log-normal variable ($C_s = 1.0$ and $C_s = 2.0$), obtained by the data generation method (Monte Carlo method): The mean, the variance and the skewness coefficient of S_n as function of q , for the above three values of C_s of x ($C_s = 0$; $C_s = 1$; $C_s = 2$), respectively as the left, central and right graph.

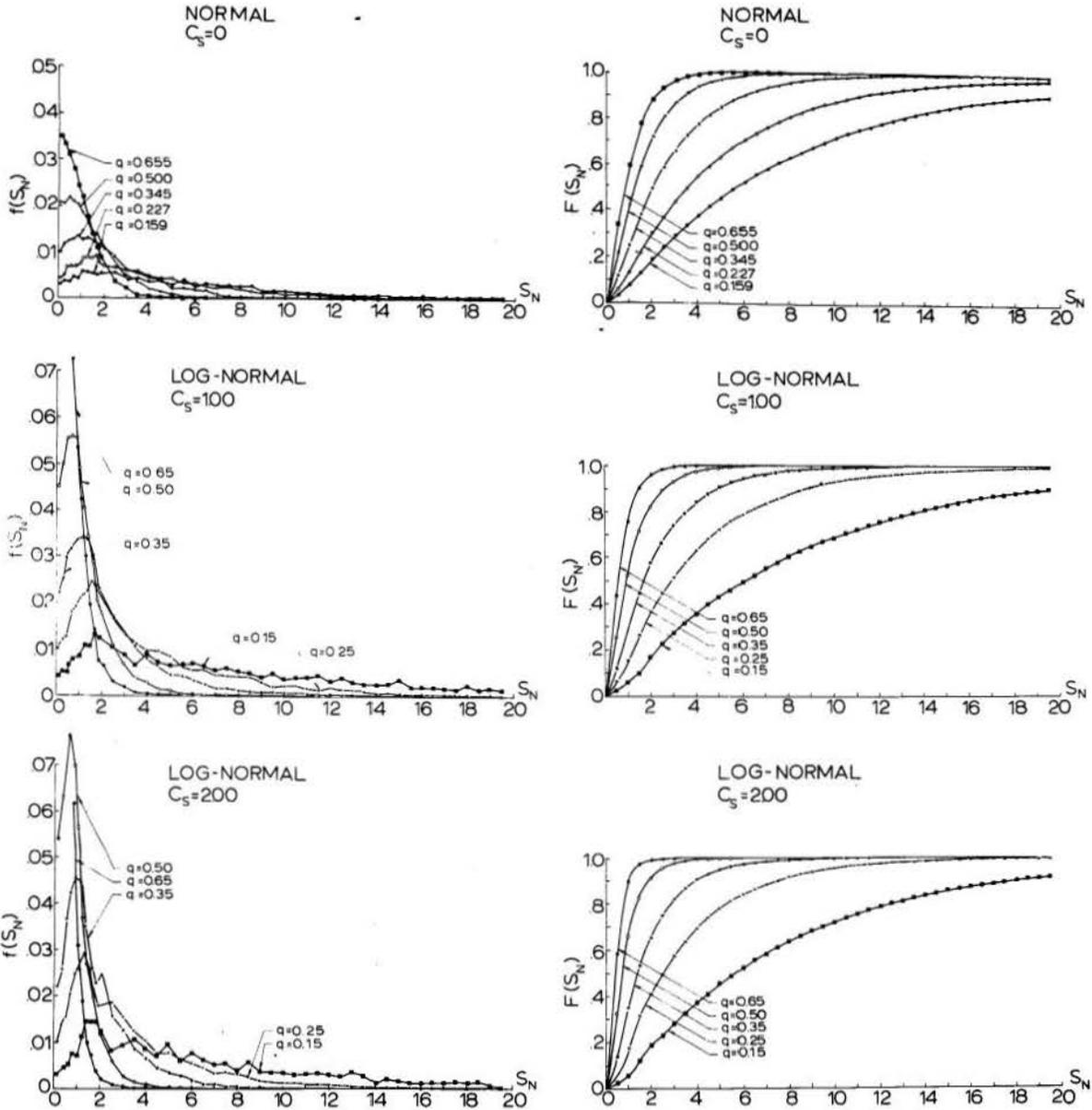


Fig. 7 Frequency curves (left graphs) and frequency (cumulative) distributions (right graphs) of the run-sum S_n of the independent standard normal variable (upper two graphs), and of the independent log-normal variable ($C_S = 1.0$, two middle graphs; and $C_S = 2.0$, two lower graphs), for five values of q (0.65, 0.50, 0.35, 0.25, 0.15), obtained by the data generation method.

CHAPTER III

DESCRIPTION OF DROUGHTS

1. Data on precipitation and runoff. A large number of observations on precipitation and runoff in many large continental regions around the world is already available. This data, if properly assembled, would enable a comprehensive evaluation of droughts. Modern digital computers, advanced statistical methods, and methods of numerical analysis make analysis of data practical. The first step in this analysis is the proper mathematical description of the two hydrologic processes: the determination of time series characteristics and the regional dependence individually for precipitation and runoff. However, many properties - at least in general lines - are already known about these two phenomena, and they will be summarized in the following text.

The basic properties of precipitation and runoff have been studied in many investigations during the last half century. They will not be reviewed here. Instead, only results obtained at Colorado State University in the last 4-5 years will be summarized.

2. Properties of series of annual precipitation. A study of serial correlation in series of annual precipitation of 1141 gaging stations in Western North America (with an average length of series of 54 years) has shown the following results [3]:

(1) The average first serial correlation coefficient (\bar{r}_1) of these 1141 stations was 0.055. Assessing that the expected mean value of independent time series of the length $N = 54$ is $E(r_1) = -0.019$, the difference is $\Delta\bar{r}_1 = 0.076$. The average values of the other serial correlation coefficients (r_2, r_3, \dots) were very small, oscillating about the expected value of -0.019 .

(2) The distribution of r_1 for these 1141 stations is close to a straight line in the cartesian-probability scales, which is expected to be the case for the normal distribution of r_1 .

(3) The slope of r_1 - distribution for these 1141 stations was nearly identical with the slope of 1141 values of r_1 for independent normal variables of the average time series length of $N_a = 54$.

A study of serial correlation in series of annual precipitation of the same 1141 gaging stations but for the same period of observations on all stations for 30 years (1931-1960) has shown similar results:

(1) The average value \bar{r}_1 of 1141 values of r_1 was 0.028, and the expected value for an independent series of $N = 30$ was $E(r_1) = -0.034$. The difference was $\Delta\bar{r}_1 = 0.062$.

(2) The distribution of 1141 values of r_1 , and its slope in the cartesian-probability scales were

similar to the previous case of the average length of $N_a = 54$ for the same 1141 stations.

The average values of $\bar{r}_1 = 0.055$ and $\bar{r}_1 = 0.028$ in the above two cases, and for very large samples of annual precipitation series, show clearly that the time dependence of successive values of annual precipitation is very low, and that those series are surprisingly very close to the independent time series.

Another sample of series of annual precipitation for 473 precipitation stations in Western North America, (therefore, a total of $1141 + 473 = 1614$ stations investigated) has been designated as non-homogeneous or with inconsistent data. Stations have been moved during the period of observations either in altitude or in horizontal position for significant distances. Tests of non-homogeneity were made in some cases [3, pages 42-44]. For these 473 stations and for the average length of series of $N_a = 55.5$ years, the value $\bar{r}_1 = 0.071$ was obtained (versus 0.055 for the homogeneous data). For $N = 30$ years (1931-1960) a value $\bar{r}_1 = 0.053$ is obtained (versus 0.028 for the homogeneous data). This sample shows that the non-homogeneity in data which was mainly produced by manmade factors of station relocations and systematic errors in gaging, increased on the average first serial correlation coefficient. Analytical study shows the similar conclusions [4]. One can legitimately assume that, among the 1141 stations considered as homogeneous, many stations may have data which are more or less non-homogeneous.

Therefore, the differences between the expected values of r_1 and the computed mean values $\bar{r}_1 = 0.055$ ($N = 54$) and $\bar{r}_1 = 0.028$ ($N = 30$) may partly be explained by the inherent non-homogeneity and inconsistency in observed data.

A conclusion may be advanced here, that for all practical purposes the series of annual precipitation are independent stochastic processes. A very small average time dependence may be explained by various factors [3], but it does not permit any significant prediction of future values. If a simple statistical technique, such as the serial correlation, cannot detect any substantial persistence in the sequence of annual precipitation on a large continental area of about 1600 stations, there is an extremely low probability that the refined statistical techniques and the use of other regions around the world and still a greater number of stations and lengths of observations would show significantly different results. Scientists in hydrology, meteorology, and other connected disciplines should adjust their attitudes and philosophies to the fact that annual precipitation at a point or over an area is nearly an independent variable. Only statistical properties of past observations can be used for the probability statements on what may occur in the future.

3. Properties of series of monthly precipitation.

A study of monthly precipitation [5] of 219 precipitation gaging stations in the United States west of the Mississippi River has shown a very instructive result. Designating the mean monthly precipitation by m_τ (12 values for each station), and the standard deviations s_τ of values of each calendar month about m_τ , it was shown that a high degree of proportionality exists between s_τ and m_τ , or that C_v is close to a constant for any given station (the newest study underway at Colorado State University supports further this conclusion). Both m_τ and s_τ follow a periodic movement, and can be approximated by the cycle of 12 months and a couple of its subharmonics. The standardization

$$y_t = \frac{x_t - m_\tau}{s_\tau}$$

where x_t are observed monthly values, produces the second order stationary time series y_t , which is free of the periodic component. The study [5] demonstrated clearly that y_t variables are very close to independent time series. In other words, the stochastic components in the series of monthly precipitation are independent variables (or nearly so).

The atmospheric processes on the earth and all factors affecting them produce a periodic movement of precipitation within the year, and on it a pure random variable is superposed. The number of harmonics needed to describe mathematically this periodic movement and the percentage of the total variance of monthly precipitation which is explained by the periodic component, depend on the location and general climatic characteristics at the position and elevation of a particular precipitation gaging station. For the Western United States the explained variance by the periodic component of monthly precipitation ranged from 0-20 percent (arid and semi-arid regions) to 40-60 percent (the wettest region of the Northwest). Therefore, the independent stochastic components represent a large portion of monthly precipitation series, especially in arid and semi-arid regions.

In summary, monthly precipitation in the future can be extrapolated only for the periodic component, while for the stochastic component one can only make statements in the probabilities.

4. Properties of series of annual runoff. A study of annual river flows of 140 gaging stations from several parts of the world [3] showed that the average first serial correlation coefficient was $\bar{r}_1 = 0.175$. By computing in an appropriate way [6] the effective annual precipitation (defined as the annual precipitation minus the annual evaporation over a river basin), this variable gave for 140 stations an average value of $\bar{r}_1 = 0.135$. No cycles were determined in the sequence of annual river flows and effective annual precipitation. Markov linear models (first and second order) fitted sufficiently well the time dependence of these two variables. The main explanation of these dependences lies [3] in the water storage effect, or the stored water carryover in river basins from wet to dry years and its release out of a river basin either through runoff or through evaporation.

A similar study [3] of annual river flow and the corresponding effective annual precipitation for

446 river gaging stations in Western North America has given the following values of the average first serial correlation coefficients: $\bar{r}_1 = 0.197$ for the annual river flow and $\bar{r}_1 = 0.181$ for the effective annual precipitation with the average time series length of $N_a = 37$. The values are $\bar{r}_1 = 0.163$ for the annual river flow and $\bar{r}_1 = 0.146$ for the effective annual precipitation in the case $N = 30$ (1931-1960 period). Explanation for these dependences consistently led to the storage and carryover of water in river basins [3]. Similarly, as in the worldwide sample, no periodicities or trends were detected. The first and second Markov linear models were satisfactory mathematical models in describing these time dependences.

The implication of the above two investigations on annual flow and annual effective precipitation is that the deterministic prediction of future values from the past observations can be made only on the basis of water stored in a river basin at a given time, but for the predominate stochastic independent variables in the Markov models only probability statements can be made for future values.

5. Properties of series of monthly runoff. A study of time series of monthly runoff for 137 runoff stations in the United States west of the Mississippi River [5] showed that the series are composed of a periodic movement for the mean m_τ and the standard deviation s_τ (with $C_v = s_\tau/m_\tau$ approximately a constant) of monthly flows, and a stochastic component of the first or second order Markov linear models. The explained variance of monthly flows by the periodic component (12-month main cycle plus a couple of its subharmonics in the Fourier series approach of mathematical description of this component) varied [5] from 0-50 percent around the Gulf of Mexico, to 50-90 percent in the wet region of the American Northwest.

As a conclusion, the periodic component and the stored water carried over in the river basins, which is responsible for the stochastic dependence of random component, can be used to predict deterministically the future monthly flows from the observed ones, while the independent random variable (the noise) will allow only the probability statement about the variation of the future monthly flows around deterministically predicted flows.

6. Daily river flows. A study of the structure of time series of daily flows [7, 8] on 17 river gaging stations in the United States has shown similar time series patterns to those obtained for the time series of monthly flows. The series are composed of periodic components of m_τ and s_τ (with s_τ/m_τ approximately a constant for each station) and stochastic dependent components, for which the dependence in daily precipitation and the water carryover in river basins determine the degree of dependence. Therefore, the same conclusions are valid for daily flows as for monthly flows, with the addition that parameters in mathematical models of components are different, and with the assertion that the series of daily flows contain more statistical information than the series of monthly flows [9].

7. Relationships between extraterrestrial phenomena and hydrologic time series. Sunspots are the best known extraterrestrial phenomena which are often related to the hydrologic processes of

precipitation and runoff. This relationship was investigated [10] between: (1) Wolf's monthly sunspot numbers and the time series of monthly precipitation of 88 gaging stations in Western United States; (2) Wolf's annual sunspot numbers and the time series of annual precipitation of 174 gaging stations in Western United States; and (3) Wolf's annual sunspot numbers and the time series of annual flows of 16 river gaging stations in Western United States. Cross-correlograms and cross-spectra have been used as techniques of investigation, and their average graphs were obtained. The conclusion is that no significant statistical evidence exists, either for the simultaneous correlation or the lag correlation, between sunspots and hydrologic time series. This would mean that there is small prospect for droughts prediction by sunspot fluctuations and their periodic component.

8. Inter-station correlation in annual precipitation and in annual effective precipitation. A study of series of annual precipitation of 1141 stations in Western North America, and a series of annual effective precipitation obtained for 446 runoff gaging stations in the same region has shown some basic patterns in regional correlation of each of these two variables [11].

The main conclusion was that the correlation coefficient of a station series of annual precipitation or annual effective precipitation with the series of other stations decreases continuously with an increase of the distance between the two stations correlated. The general correlation pattern was a bell-shaped space surface for the correlation coefficient expressed in terms of the distance from the central station. The greater the distance, the closer the correlation coefficient is to the expected value of zero.

It was also found that for all practical purposes, the two series of annual precipitation become independent among themselves if the distance between stations is approximately 800-1200 miles or greater. There was no evidence that a second or third wave of significant dependence reappears beyond 1200 miles, though the continental area of Western North America was not sufficiently large to investigate this potential dependence.

It was also found [11] that meteorologic and hydrologic factors which cause the inter-station correlations in the above two variables studied were not isotropic, because the isolines of equal inter-station correlation coefficients about a given point were well approximated by ellipses and not by circles. This means that in the direction of the greater axis of ellipses, the correlation coefficient decreased more slowly with distance than it did in the direction of smaller axis. However, the orientations of the axes of maximal and minimal correlations do not afford a ready means of tracing the flux of atmospheric moisture or a means of identifying its sources. The inter-station correlation coefficients in annual effective precipitation were on the average somewhat greater than those for annual precipitation. This must be a result of evaporation patterns. However, there was more variability in the correlation coefficient of annual effective precipitation than in that of annual precipitation.

It is noticed that the large mountain barriers, such as the Rocky Mountains, have a significant effect on regional correlation between the series of annual precipitation, annual effective precipitation, and annual runoff. The decrease of the correlation coefficient with the distance is more rapid than in the

adjacent plateau regions, and the elliptical patterns of isolines of correlation coefficient, with a consistent direction of maximal and minimal axes, are disrupted in mountains and around them.

The above summary of results of this study [11] points out to some of the basic properties of large continental droughts. The high regional correlation among series of annual precipitation and among the series of annual effective precipitation (and also among the series of annual runoff at adjacent small and medium size river basins) indicate these properties:

(a) It is impossible to get severe droughts in very small areas;

(b) The average areal coverage of severe large continental droughts is of the order of a diameter of 1500 - 2500 miles;

(c) The more severe a large continental drought, the larger is its areal coverage;

(d) The area covered by a drought is expected to be closer to an ellipse than a circle;

(e) In high mountains the correlation is disrupted in several ways, but basically it decreases faster with distance, and directions of correlation axes are less subject to clear patterns.

The regional correlation patterns enable the use of the data generation method for drought description very effectively. Once a center station time series of annual precipitation is generated, the proper use of regional correlation can be used to generate the time series at other stations, which will have the necessary correlation with the central station and several adjacent stations, plus the random variable added.

9. Conditional regional probabilities of annual precipitation. In the study on conditional probabilities of occurrence of wet and dry years over a large continental area [12], the annual precipitation time series of stations in Western North America were used, and conditional probabilities were determined. Various mathematical models were fitted, and particularly: independence model, exponential dependence model, linear dependence model, and hyperbolic dependence model. They produced the conditional probabilities as functions of distance from the central station, usually with two or three parameters to be estimated from data. The conditions under which each model best fits the data were determined.

The determination of conditional probabilities of regional occurrence of wet and dry years over the area [12] repeats the results of the study on regional correlation [11], but adds a significant contribution. It shows a good understanding of interrelationship among the series of annual precipitation in a region.

10. Statistical versus deterministic description of droughts. The above summary of several studies refers basically to the statistical studies of hydrologic phenomena, which enables the computations necessary for the statistical description of large continental droughts. The physical conditions and various analyses of synoptic situations which are responsible for these droughts are less amenable to a rigorous analysis, both because of the lack of sufficient data and because of complexity of interrelationships. The conditions which prevail over the region of continental droughts and around it are easy to identify and eventually describe, but why those

conditions occurred and the means to anticipate them with a sufficient time lag is not easy to determine, and outlook for such predictions is not very encouraging.

If the sequence of annual precipitation is an independent hydrologic process, or nearly so, how can one expect to ever predict the large continental droughts of several years duration, if another independent process in the nature does not precede it for a sufficient time lag, and is amenable to observations? It is, therefore, necessary to follow the following three lines of investigation for the description of large continental droughts:

(a) Statistical description, in assigning the probabilities of occurrence (or frequencies, or return periods) of droughts for given areal extension, time duration, and severity of moisture deficit below the critical moisture level;

(b) Physical description of synoptic situations of atmosphere, adjacent oceans and seas, and the continental areas attacked by drought, which existed during the drought, preceding and following it; and

(c) Description by computing the interrelationships between various synoptic situations in search of dependences either by time lag correlations or by physical relationships. This last case is not only important for the description of droughts, but also for their explanation and eventual development of methods for their prediction.

11. Shape of drought runs. The runs of a drought may have various shapes. These shapes are important for water users, and it is necessary to develop an approximate classification of drought shapes. They can be referred either to time duration or to areal extension or to both for a given value of the level of critical moisture supply, x_0 .

Referring only to the time runs, fig. 8 shows some of the typical shapes: a growth of deficit to its point of maximum, and then a slow decrease to zero (1); an early deep deficit and then a slow decrease (2); a slow increase and a late high deficit (3); a nearly constant deficit (4); a time run divided into parts, with a start of drought, then easing and again deepening (5) and (6), as a non-continuous drought, such that even a small positive run may occur between deficits.

This classification may be quite arbitrary. For the same values of a run-length and the corresponding run-sum, the probabilities of various shapes of time runs are not equal. The reasons are simple. The various negative deviations from x_0 are of different probabilities, and some shapes are less likely than others.

Similarly, shapes of areal coverage by droughts (shape of area limited by the isoline of zero deficit) may be different, and for the same areal coverage some shape may be more likely than others.

Descriptions of droughts in the form of shape of time runs and shape of area covered by droughts has been done mostly by purely qualitative description. However, any classification of droughts by these shapes and by probabilities attached to them, for

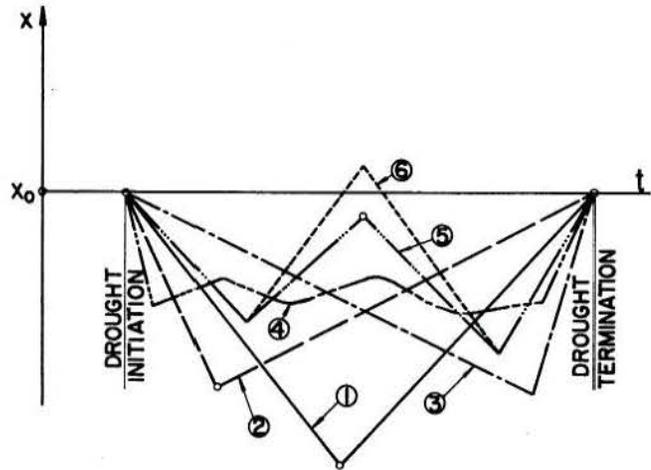


Fig. 8 Various shapes of drought time-runs: (1) slow growth with a slow decrease to the maximum water deficit; (2) early deep deficit and its slow decrease; (3) slow increase with a late maximum deficit; (4) a nearly constant deficit; (5) time-run divided in two parts; and (6) time-run divided by a very small positive run.

given properties of time runs and areal coverage, should be based on objective definitions, and described by parameters which define these shapes (variation about the line of the mean deficit, skewness coefficient about the mean time of run-length, and similar parameters). How important these descriptions are depends on the significance of drought studies and their economic implications.

12. Effects of droughts. The assessment of drought damages and consequences has the same characteristics as the assessment of flood damages and consequences. That is, there are direct and indirect economic and social losses, with the difference that drought effects and damages are slow in building up and are persistent, while flood effects usually show faster time effects.

Methodology in computing direct losses and estimating indirect consequences of droughts is not well developed, and less so than is the case with flood losses. Indirect effects of protracted large continental droughts are difficult to assess, because they involve large areas and many social activities. The chain reaction of economic and social consequences of a large area agricultural drought is a well known example.

Description of large continental droughts from the point of view of various economic and social consequences is a prerequisite for any policy in combating large droughts. With time the economic development, the increase of population, and the larger pressure on the water available in a region will inevitably increase the economic and social consequences of large continental droughts to such an extent that the political pressure will force the design of policies for combating droughts. Therefore, the time may be appropriate for designing the necessary methodology of drought description by its economic and social effects as well as its psychological effects.

CHAPTER IV

EXPLANATION OF DROUGHTS

1. Causal factors related to atmospheric circulation. The explanation of droughts depends on the general hydrometeorologic characteristics of the region of drought. If the bulk of precipitation and the resulting runoff is produced by a limited number of large storms, then the lack of a sufficient number of these storms may be the main causal factor of droughts. The next causal factor is the decrease in moisture productivity of storms. The decrease in the number and the productivity of precipitation producing storms represents the crucial causal factors of droughts from the hydrometeorologic point of view.

The answers to questions as to why the number of storms has decreased or why their productivity have been diminished over a period of years represent the main explanation of droughts. There is a tendency to search for the explanation of droughts in the small scale evolution of atmosphere, but mainly in the general patterns of atmospheric circulation. This approach seems feasible for individual storms of short time periods. It is less likely to explain the long-range drought by finding the causal factors in the atmospheric circulation.

2. Causal factors related to oceanic circulation. The distribution of cold and warm ocean areas and their evolution in time, may produce a larger time lag for the anticipation of the number and productivity of precipitation storms. There is positive correlation between the average surface sea water temperature west of California and the average precipitation at the Sierra Nevada Mountains. These causal factors of oceanic parameters affecting the moisture supply to the atmosphere are the best outlook for the explanation of droughts.

The cold Atlantic shelf waters, persistently located east of New York and New England in the last six years, may partly explain the drought of the Northeast coast of the United States. Several other examples may be found where a relationship exists between some oceanic conditions and the moisture deposition over the related continental areas.

3. Causal factors related to continental areas. Similarly as the occurrence of particular cold and warm ocean areas may precede the drought over some

continental areas, the cold continental areas (areas covered by snow and ice), or very warm continental areas, may precede or produce the occurrence of drought over the adjacent continental areas. The snow and ice covers change not only from one season to the next, but also from year to year.

The negative correlation often experienced between the summer precipitation and summer temperature over cold areas may be responsible either for a large retreat or a substantial advance of the snow and ice edges of polar regions. Once the ice edge advances sufficiently, the retreat to the average position requires time. Similarly, a retreat of ice edge far toward the poles because of the occurrence of several dry but warm summers requires several years to return to the original position. This advance-retreat-advance process, with the feedback mechanism, may be the reason for large drought occurrence over continental areas. The explanation of droughts may well be searched for in the above and some other similar continental stochastic phenomena.

4. Research needs for explanation of droughts. Several large continental droughts have been already observed in the last 50-70 years, which can be the basis for attempting their explanations, such as: the large mid-west drought of 1930's, especially in the Missouri River Basin, the recent 6 years long drought of the United States Northeast, and others. This research may be hampered by lack of sufficient information on atmospheric, oceanic and continental causal factors of these droughts. However, some information, at least rudimentary, is available on the potential causal factors so that the research attempts for the discovery of appropriate relationships are warranted.

It should be noticed that the investigations for drought descriptions, as outlined in the previous chapter, and those for the explanation of droughts, as described in this chapter, are overlapping if not identical in many aspects. The explanation of droughts is mainly related to the physical interrelationships of the cause-effect type, while the description of droughts encompasses both the statistical and deterministic characteristics.

CHAPTER V

PREDICTION OF LARGE CONTINENTAL DROUGHTS

1. Complexity of the problem of prediction. As previously emphasized, the predominately random character of series of annual precipitation, annual effective precipitation and annual runoff does not give any promising outlook for the auto-prediction of droughts. Auto-prediction is defined here as the extrapolation of patterns of past observations to predict uniquely (not in probability terms) the future annual values, an approach which seems definitely ruled out by the present knowledge of the structure of hydrologic time series. In the case of monthly and daily values, the periodic components of time series and that part of the stochastic component which depends on the water already stored in river basins can be anticipated with sufficient accuracy. However, the auto-prediction approach cannot yield any unique value for the independent variable of the stochastic component.

The other approach to drought prediction is the search for those factors, usually of the same structure of time series as the related precipitation and runoff, which precede the occurrence of precipitation and runoff. Of particular interest are those factors which have the longest time lag preceding the resulting hydrologic phenomena. The problem is complex because the search for this kind of preceding factors requires a tremendous amount of basic data.

2. A meaningful approach to predictions of large continental droughts. The comparison of successive synoptic situations of oceanic conditions affecting the water cycle and the precipitation synoptic situations over the large continental areas is likely to be the first reasonable step in producing meaningful relationships involving the time lags between these synoptic situations. The refining approach would come in the second stage, when the air-water interface phenomena over the oceans and the general patterns (especially the prevailing winds) of atmospheric circulation would be added.

This approach requires a tremendous amount of data on oceanic surfaces and on continental precipitation situations in the first phase of analysis, and even more data as soon as the atmospheric circulation is added in the second phase of analysis. This search for relationships between various synoptic situations, with the expected time lags for one situation preceding the other, becomes the only hope for a long-range prediction of droughts.

The basic differences between the approach advocated in this chapter and current approaches for general weather prediction are obvious. The "weather-watch" and similar programs are based on the idea that the integration of dynamic equations of atmosphere, with a sufficient number of observation points capable of defining the initial and boundary conditions, will result in the weather prediction of a significant time span. The more points of atmospheric conditions that are observed and the more powerful computers that are used, the better and longer prediction is expected. The present expectation of weather prediction by this approach is likely to be much greater than the final realization of its capabilities. The reason is simple. The phenomena of turbulence and various types of medium or large scale vorticities are predominant factors in the atmospheric circulation and are governed by the laws of probability. They are not easily subject to deterministic prediction. One should be able to see the natural limits of deterministic prediction in atmospheric circulation, and particularly of phenomena which affect the long-range prediction of precipitation. It can be claimed, with many valid arguments, that the "weather-watch" is not likely to produce any substantial contribution to drought prediction. Therefore, the approach advanced here of first looking into the time lags between synoptic situations of oceans and the synoptic situations of continental precipitation warrants a fair trial.

CHAPTER VI

MEASURES FOR COMBATING LARGE DROUGHTS

1. Engineering measures. The alleviation or substantial decrease of the adverse effects of large continental droughts is a problem for which the proper answers have not yet been found. The three basic alternatives are:

(a) Reduce the consumption of water by the appropriate economic and engineering criteria during any severe drought;

(b) Implement the drought contingency plans with additional water supply from available sources; and

(c) Provide improvised supply lines by temporary structures, and use either the transfer of water from distant regions or the previously untapped stored water in economically marginal storage spaces.

Combinations of these three alternatives usually result in the most economic solution. Reduction in consumption is the easiest to suggest though the least attractive from the aspects of social and political implications and pressures. It is a fact of life that neither a region, nor a large city or a group of cities, nor entire states have contingency plans for combating drought. Planning these contingency measures is not expensive. Small investments through the years into water systems which are already available, according to these contingency plans, may result in a substantial reduction of drought effects. The psychologic factors are important. Funds for serious studies of floods and droughts and for the planning and even investment to fight their effects are usually available when the serious events have already occurred. Cuts in these funds are proportional to the time elapsed from the occurrence of these extreme events. Contingency plans are very rarely finished, and if completed, their major recommendations and requirements are slowly implemented. The improvised solutions for water supplies from the sources available around the area stricken by a drought are rather a rule than an exception. It is normal to expect that any improvisation will have higher cost or smaller yield for the same effect than any planned measure by the drought contingency plans.

2. Transfer of water at large distances by the shifting method. The implementation of the concept of water transfer from one region to the next, in a shifting pattern similar to the shifting of electric power over long distances, merits a thorough investigation. The concept is illustrated in fig. 9 as a schematic example. Area E, assumed to be drought stricken, would be supplied by a quantity of water W from the area A, which would have a sufficient water surplus during the drought in area E. The distance between A and E would be of the order of 1000-1500 miles, and the more severe a drought, the greater would be that distance. Several routes of water shifts are available, and two routes are schematically shown in fig. 9.

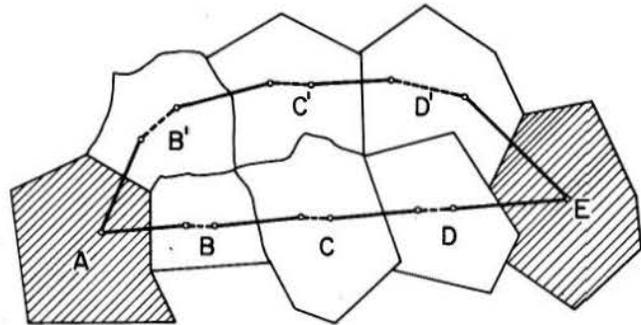


Fig. 9 A conception of supplying water deficit to drought-stricken area (E) from the water surplus area (A) by the method of local shifts of water from one sub-area to another.

This concept would not require any water from the areas B, C, and D, but might require the supply of a part of each of those areas by the water from the adjacent area and the transfer of the same amount from its other parts to the next area. Areas B, C, and D would only help the general transfer from A to E, by using the advantages of the topography, the feasibility of water distribution between sub-areas, the elevation and the available conveyance facilities in areas B, C, and D.

To implement such a concept a network of water conveyance structures should cover, in the appropriate way a large continental area, as electric transmission lines or gas transmission pipes now cover the similar area. This concept may prove, in the long run, to be the most economical way for combating droughts on a large subcontinental scale. One would expect, with good reason, that very careful planning and a long-term investment policy are necessary in order to accomplish this goal. The basic problem lies with the objectives and principles of every substantial project of water resources planning and development. The single purpose project gave way to multipurpose water resources projects. Economy forced this transition. The multipurpose project gave and is currently giving way to river basin integrated water resources planning. This concept in turn must give way to large regional and inter-regional water resources planning. Besides the forthcoming water shortages of many areas, the ever-impending threat of drought will be the stimulating factor which will force this large continental water resource planning. It will then be much more feasible to accomplish the task of providing a grid of interconnected water conveyances over a large area over a period of several decades.

If large and severe continental droughts have recurrence intervals of a couple of decades, the planning and carrying out of investments of contingency

plans for drought combat on this large scale should also allow decades for implementation. There is another important point in this alternative. If properly designed conveyance structures to be run under water pressure (tunnels, pipes) were available, the use of auxiliary pumping plants, --which may be movable as the emergency equipment--, might temporarily increase their capacities in the case of droughts. Several other engineering concepts may well be incorporated into plans for drought emergencies.

Proposals of large-scale and long-distance water diversions have been advanced for the North American continent in recent years. They usually emphasize only the benefits of the average water diversion. Their role in stabilizing the water supply by their potential of emergency water supply to drought-stricken but normally self-sufficient areas along and adjacent to the routes of diversion is less advocated. Yet that role may substantially add to the feasibility of proposed projects.

3. Drought insurance. To develop any sound long-range policy of combating drought consequences on the basis of drought insurance, either by public or by private institutions or by both simultaneously, much more should be known about the droughts, and particularly about their recurrence, potentials for prediction and various alternatives for combating the drought. Similarly as for the problem of flood insurance, central public authority is the last resort for the coverage of drought losses. Uncertainties involved in the knowledge available on floods and droughts have always been limiting factors in any conventional insurance approach against their consequences.

It should be expected that any systematic research which could contribute to the understanding of various facets of large continental droughts would unavoidably lead to new policies in drought insurance, both by public or private institutions.

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Key Words: Drought, Runs, Prediction of droughts

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