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CHAPTER 7
DROUGHT PREDICTION: A HYDROLOGICAL PERSPECTIVE

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INTRODUCTION

To predict a drought, a hydrological perspective is not enough. Hydrological processes are among the final steps leading to drought; it is through them that the phenomenon of drought is eventually revealed, usually long after its original causes have been obscured.

In order to predict drought (or to come to a conclusion that this is impossible), we must understand its causes. This means tracing those causes back, indeed very far back, perhaps even to the two penultimate sources of energy powering the climatic engine: the solar processes whose fluctuations, transmitted through solar-terrestrial relations at a variety of energy levels, constitute one set of boundary conditions for the atmospheric processes; and the processes in the earth's interior, which--through geological, geophysical, and oceanographic phenomena--represent the other set.

The synthesis of these two sets of processes, superimposed on the geodetically complicated motions of the earth and modified by extremely complex feedbacks through the biosphere, then produces the irregularly fluctuating climate. This climate is made up of the short-term fluctuations of atmospheric processes that constitute the domain of meteorology. Of these processes, precipitation is the immediate carrier of the "drought signal." For the meteorologist, the drought "buck" stops right here and so it does for all those whose water supply comes directly from precipitation. At the meteorological level, drought is essentially equivalent to a long absence of precipitation.

But there is one more level down the road, the hydrological level. In general, lack of precipitation is not always sufficient to produce drought. Obviously, drought never occurs in the open ocean even if there is no precipitation at all. Similarly, it would be difficult to talk about drought in circumpolar permanently glaciated regions such as those in the Antarctic or Greenland. In order to produce drought, a lack of precipitation over some life-supporting land surface is necessary. However, even this is not sufficient, since precipitation is not necessarily the only direct source of water for every water user: water can also be, and very often is, supplied from storage.

The case of the open ocean is useful to illustrate these basic points. Even in the open ocean a "drought" can arise if we insert there a piece of life-supporting "land surface" in the form, say, of a lifeboat with a shipwrecked sailor. He obviously could have a drought problem, but only after his supply of drinking water has run out. This simplified example highlights the most important fact: even the absence or lack of water as such is not enough to cause a drought--it must pose danger to some form of life. There would be no drought problem in our lifeboat if there were no sailor in it.

This sociobiological aspect is implicit in the very term *drought*; otherwise we would be concerned merely with the lower tail of the statistical distribution of water on the land surface. In the interest of accuracy it should be noted that only the latter problem constitutes the subject matter of hydrology. Strictly speaking, drought is not a hydrological phenomenon; for hydrology, drought is an *effect* of low states of water on some nonhydrologic system, specifically on some life-supporting process that is in some way important to mankind.

To summarize, hydrology takes over from meteorology as the study of water distribution on the land surface after precipitation has reached the ground. In hydrology, precipitation is only an input to be processed. It concentrates on the processes that redistribute this input into various natural storages available on land, on the fluctuations of water in these storages, and on the outflow processes associated with them. In short, the interest of hydrology is focused on processes related to water storage. Hence it has the greatest potential for contributing to the study of drought and to its prediction in those instances where drought results as a consequence of shortages in water supply from natural land-based storage systems.

For the purpose of this discussion, hydrologic storage systems can be divided roughly into three categories:

1. Surface water, representing the water in lakes, depressions, and rivers.
2. Subsurface water in the unsaturated strata, including the soil moisture.
3. Ground water, which is all the water present in the saturated strata.

The differences between these storages are important for two reasons. First, water available from each tends to serve a different purpose and thus its shortage leads to drought symptoms in different areas. Second, their outflow or release processes are dominated by different types of mechanisms, so that the patterns of their fluctuations, and hence the patterns of droughts related to them, are often different.

From this short outline, it should be obvious that hydrology can contribute to the study and prediction of drought mostly by shedding light on the changes that hydrological storages introduce into the patterns of temporal and spatial distribution of water, patterns that have been set by the distribution of precipitation. For the understanding and possible prediction of the precipitation patterns themselves, one must turn to meteorology, climatology, and other disciplines in the hierarchy of processes mentioned earlier.

The Long-Term Perspective

Hydrology can do little to predict droughts far in advance or long periods of drought. But it can contribute significantly to the understanding of why such predictions may be difficult, perhaps even impossible.

Prediction in real time, referred to as *forecasting* in hydrological usage (*prediction* is used only in connection with an unspecified lead time, generally for predictions of statistical frequencies), is possible only if the phenomenon to be forecast exhibits some deterministic pattern. For long-term drought forecasting, the main prerequisite for success is a discovery of trends or periodicities in the climate that could be traced to some underlying deterministic processes in the hierarchy outlined earlier. The two strongest candidates for such processes have been those underlying the formation of sunspots and those triggered by geodetic motions of the earth.

The literature trying to establish a correspondence between these two types of periodicities and the fluctuations in rainfall, river runoff, lake levels, and glaciers is extensive in volume but very modest in conclusive evidence. Most of it relies on statistical correlations between records of the various water-related phenomena and the sunspot numbers or the computed solar energy fluctuations attributable to the geodetic motions. Although these correlations may sometimes seem impressive, there is a conspicuous paucity of documented physical mechanisms that could supply the necessary causal linkages. Without such mechanisms the origin of the apparent cyclic features in hydrological time series must be treated with extreme caution. This is because a hydrological process almost always reflects some kind of storage mechanism and a storage mechanism almost always exhibits what has been called pseudocyclic or quasi-periodic behavior even when it operates on a perfectly random input.

In mathematics the storage feature has been known for a long time. However, in mathematics the counterpart of the physical operation of "storing" is the operation of summation, integration, or cumulation, and the phenomenon of pseudocyclicity has been described in connection with these mathematical operations (Slutzky, 1927; Feller, 1966) rather than with the physical process of storing. Improbable as it sounds, theorists working on storage processes, whether in mathematics, engineering, or hydrology, somehow have failed to make the connection. Moreover, many hydrologists have difficulty appreciating the fact that most hydrological processes actually themselves represent the storage or "cumulative" processes. They tend to take the "cyclic features" in these processes at their face value and engage happily in fitting cyclic features with the most sophisticated mathematical constructs, for which there is little physical justification. These problems were discussed in detail more than a decade ago (Klemeš, 1974) and are still relevant.

Since an understanding of the cyclic behavior of geophysical processes in general, and hydrological processes in particular, is crucial to long-term drought prediction, it may be useful to illustrate the main aspects of the aforementioned issues.

Consider a sequence of random numbers. An example of such a sequence, x_t, $t = 1, 2, \ldots, 50$, appears in the second column Table 1 and its plot is shown in Fig. 1A. The numbers come from a population that is uniformly distributed between one and one hundred (Neville and Kennedy, 1964). Suppose that the variable x represents annual precipitation totals in mm. Because our series is purely random, we know that it is impossible in principle to forecast the time of occurrence of a "drought" or its length. Suppose, however, that our "precipitation" series is a real observed record, so that we do not know whether it is a random series or not. In the search for a pattern that would enable us to forecast droughts, we subject the series $\{x\}$ to various types of manipulations and analyses. One of the most common and simple analyses is to make a plot of the cumulative departures from the mean, $y_t = \sum_{i=1}^{t} (x_i - \bar{x})$, as computed in column 4 of Table 1 and plotted in Fig. 1B. Unlike the original series $\{x\}$, its "residual mass curve" $\{y\}$ (as the type of plot shown in Fig. 1B is also known) strongly suggests the presence of cycles, which may encourage us to extrapolate them, correlate them with cycles in other

Table 1

Fifty Uniformly Distributed Random Numbers x_t ($t = 1,2,\ldots\ldots,50$) and Their First and Second Order Cumulative Sums of Departures from Mean (residual mass curves), y_t and z_t

Order Number	Random Number	Diff.	Cumulative Sum	Diff.	Cumulative Sum
t	x_t	$x_t - \bar{x}$	$y_t = \sum_{i=1}^{t} (x_i - \bar{x})$	$y_t - \bar{y}$	$z_t = \sum_{i=1}^{t} (y_i - \bar{y})$
1	98	48	48	28.64	28.64
2	25	-25	23	3.64	32.28
3	37	-13	10	-9.36	22.92
4	55	5	15	-4.36	18.56
5	26	-24	9	-28.36	-9.80
6	1	-49	-58	-77.36	-87.16
7	91	41	-17	-37.36	-123.52
8	82	32	15	-4.36	-127.88
9	81	31	46	26.64	-101.24
10	46	-4	42	22.64	-78.60
11	74	24	66	46.64	-31.96
12	71	21	87	67.64	35.68
13	12	-38	49	29.64	65.32
14	94	44	93	73.64	138.96
15	97	47	140	120.64	259.60
16	24	-26	114	94.64	354.24
17	2	-48	66	46.64	400.88
18	71	21	87	67.64	468.52
19	37	-13	74	54.64	523.16
20	7	-43	31	11.64	534.80
21	3	-47	-16	-35.36	499.44
22	92	42	26	6.64	506.08
23	18	-32	-6	-25.36	480.72
24	66	16	10	-9.36	471.36
25	75	25	35	15.64	487.00
26	2	-48	-13	-32.36	454.63
27	63	13	0	-19.36	435.28
28	21	-29	-29	-48.36	386.92
29	17	-33	-62	-81.36	305.56
30	69	19	-43	-62.36	243.20
31	71	21	-22	-41.36	201.84
32	50	0	-22	-41.36	160.48

33	80	30	8	-11.36	149.12
34	89	39	47	27.64	176.76
35	56	6	53	33.64	210.40
36	38	-12	41	21.64	232.04
37	15	-35	6	-13.36	218.68
38	70	20	26	6.64	225.32
39	11	-39	-13	-32.36	192.96
40	48	-2	-15	-34.36	158.60
41	43	-7	-22	-41.36	117.24
42	40	-10	-32	-51.36	68.88
43	45	-5	-37	-56.36	9.52
44	86	36	-1	-20.36	-10.84
45	98	48	47	27.64	16.80
46	0	-50	-3	-22.36	-5.56
47	83	33	30	10.64	5.08
48	26	-24	6	-13.36	-8.28
49	91	41	47	27.64	19.36
50	3	-47	0	-19.36	0.00
Sum	2,500	0	968	0.00	
Mean	$\bar{\chi} = 50$		$\bar{y} = 19.36$		

series, and so forth. This, of course, all would be in vain if the original series were random (as it actually is), because the cycles in the mass curve $\{y\}$ are just a typical example of "the summation of random causes as the source of cyclic processes," as is pointed out in the title of Slutzky's 1927 paper, mentioned above. On the other hand, in a true precipitation series, the cycles (or perhaps some of them) could be real. The point is that the pattern itself can in no way tell whether it is spurious or real--this can only be judged by the presence or absence of evident physical mechanisms behind the pattern.

The difficulty of the problem increases as we move from precipitation records to records of hydrological processes, which by themselves already reflect the effect of some hydrologic storage and thus, in their raw form, already represent cumulative processes or include them as their components. Consider, for example, a hydrological series represented by a record of levels in a hypothetical closed lake whose only input is the random "precipitation" series $\{x\}$ displayed in Fig. 1A and whose only output is evaporation. For simplicity, let's assume that the evaporation is constant and equal to the mean of the precipitation, $\bar{x}$, and that the lake has steep banks so that its area does not appreciably change with the lake level. In such a case, the lake level series would be identical with the precipitation residual mass curve $\{y\}$ in Fig. 1B. The storage in the lake physically performs the summation of the residuals that was carried out arithmetically in Table 1--it accumulates the differences between the precipitation inputs x_t and evaporation $\bar{x}$ so that we can "leave the computation" to the lake and get the results by taking a record of its levels y_t. Thus, in this case, already the *original* "hydrological

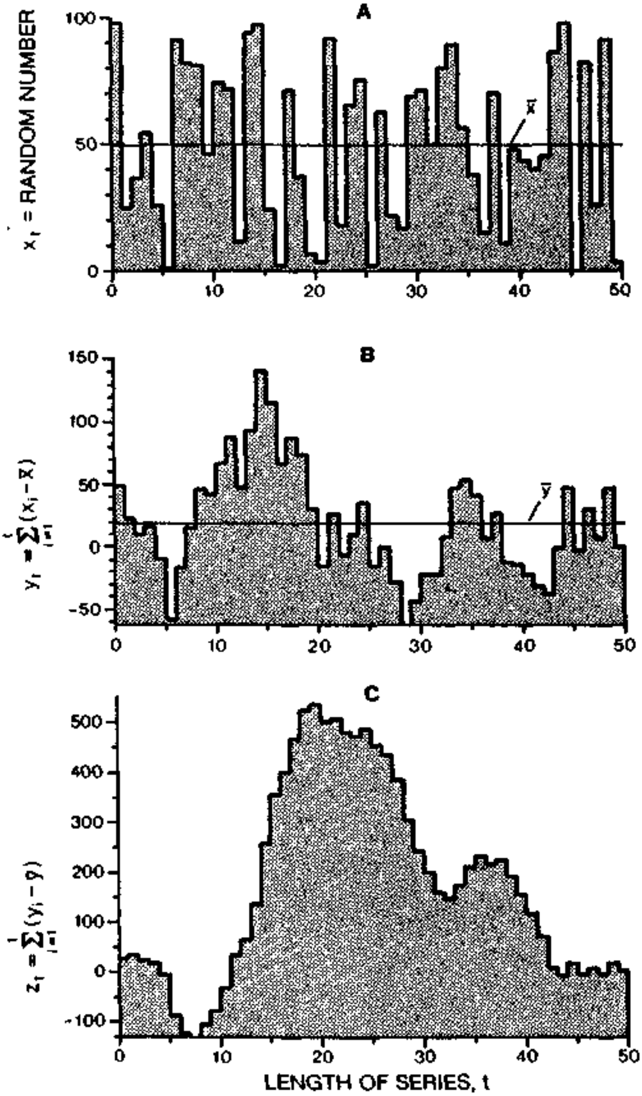

Fig. 1 Series of fifty random numbers x (A), and its first-order (B) and second-order (C) residual mass-curves, y and z, respectively.

record" {y} seems to exhibit a cyclic pattern. We of course would process this "raw" record mathematically and would perhaps again compute its residual mass curve {z}. This has been done in the sixth column of Table 1 and the plot is shown in Fig. 1C. It is apparent that the process {z} has a still more pronounced cyclic pattern than the underlying lake-level record {y}. Yet, we know that no deterministic periodic mechanism is involved here; we observe just pseudocyclic behavior of a "second order" produced by the strengthening of a pseudocyclic pattern of the "first order" by one more integration. Repetition of this operation would lead to further strengthening of the cyclic pattern; indeed, an nth order residual mass curve rapidly converges to a sine wave (Klemeš and Klemeš, 1987).

Thus, in general, hydrological series have a tendency to exhibit more pronounced and smoother cycles than precipitation series. They pose a greater danger for those who suffer from the myopic inclination to search for cycles merely by mathematical processing of time series divorced from an understanding of the underlying physical processes.

The following two quotations illustrate that mathematicians (the good ones) have been aware of these dangers much more acutely than physical scientists and engineers, who (one would assume) should be those with a more deeply ingrained tendency to base their analyses on an understanding of physical causality, as opposed to purely mathematical manipulation. More than thirty years ago, M. S. Bartlet, the eminent English statistician and probabilist, warned that "unless the statistician has a well-defined and realistic model of the actual process he is studying, his analysis is likely to be abortive" (quoted from Klemeš, 1978). More than twenty years ago, William Feller had this to say in regard to the pseudocyclic behavior of cumulative processes: "Most stochastic processes in physics, economics, and education are of this nature and our findings should serve as a warning to those who are prone to discern secular trends in deviations from average norms" (Feller, 1966).

Examples of cumulative sums of deviations from the mean for 100-year-long annual streamflow series of three European rivers are shown in Figs. 2a, 2b, and 2c; for comparison, examples of similar sums for three random series of the same length, drawn from the same gamma-distributed population, are shown in Figs. 2d, 2e, and 2f.

The Short-Term Perspective

Hydrology has a great potential for short-to medium-term forecasting of the so-called hydrological droughts (i.e., low stages in and low releases from hydrological storage reservoirs). Taking the precipitation process as an input, hydrology studies the distribution of precipitation into the different types of storages in a river basin, and interaction among and releases from those storage types. In doing so, hydrology not only can assess the impact of low precipitation on the various hydrologic processes and thus forecast the arrival and severity of a drought, but it can also contribute to a better understanding of the drought phenomenon in general and explain some of the apparent inconsistencies and differences in drought perceptions reflected in various disciplinary views and definitions as recently reported, for example, by Wilhite and Glantz (1985; also reprinted in this volume).

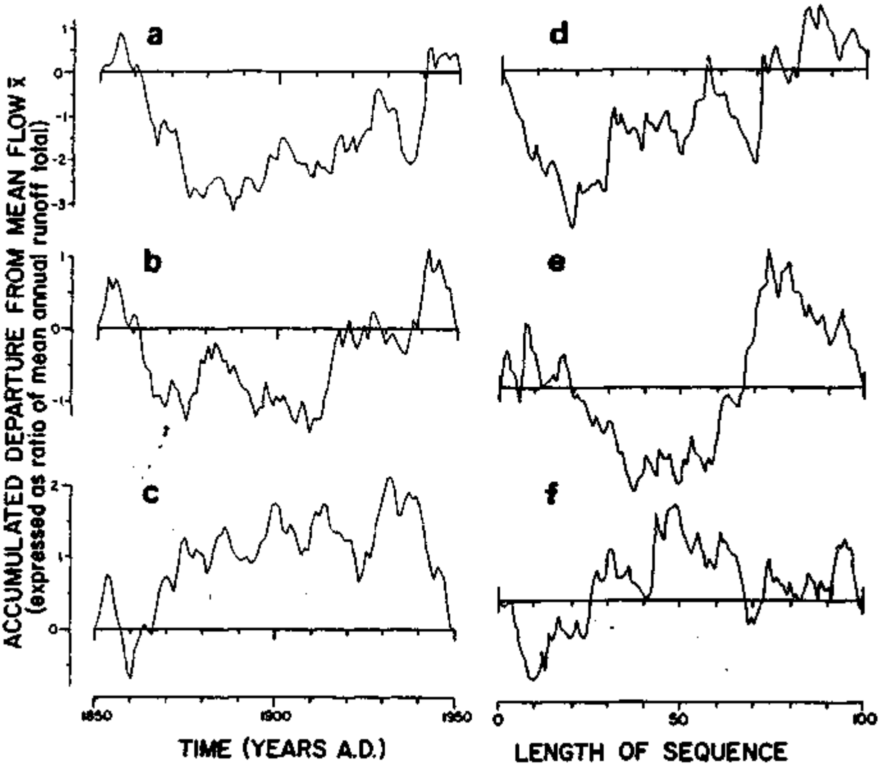

Fig. 2 Residual mass curves of three 100-year series of mean annual flows and of three samples of 100 random numbers: a—Elbe River, Děčín, Czechoslovakia; b—Danube River, Orsova, Romania; c—Gota River, Vanersborg, Sweden (from Klemeš, 1982a); d, e, f—random samples.

The key to unlocking the potential of hydrology is a thorough appreciation of the fact that hydrological processes, being affected by storage mechanisms, are often related much more closely to some integral of the precipitation input process than to this input process itself. The second most important factor is an awareness of the differences between the mechanisms operating on the different types of hydrological storages, which may result in different drought patterns in the respective processes.

To illustrate the first point in general terms, we may first note the difference between a function and its integral for two simple mathematical functions that represent typical idealized prototypes of the precipitation process. One is a sine wave that reflects the basic features of the common seasonality within the annual cycle and is changed into a cosine wave by integration. Thus a physical integrating device with a sine input would produce a cosine output. In other words, the system would introduce a $\pi/2$ phase shift into the input process. Another useful function is the Dirac delta function, defined as an instantaneous impulse of a unit magnitude. On a short time scale, it displays the basic feature of a sudden rainfall burst during a rainless period; on a longer time scale it shows a short period during which precipitation is significantly higher (or lower) than "normal." On integration, the delta function becomes a step function, thus indicating that, for instance, a couple of extremely precipitation-deficient years may introduce a downward jump in the equilibrium level of some hydrological process. In other words, a short "meteorological drought" may trigger a long-lasting period of "hydrological" drought.

The effect of reservoir storage on inflows confirms these generalizations of the features of integration. In hydrology and hydraulics, the transformation of reservoir inflow into outflow by the storage mechanism is usually referred to as storage, or reservoir, "routing" (for a comprehensive review of reservoir routing, see Klemeš, 1982b). Figure 3A shows how a typical "flood wave" might be routed in the course of its passage through a small or large reservoir system such as a cascade of lakes or a ground-water basin; in this case, the time scale would typically be such that the duration of the inflow wave would be between several hours and several days. By inverting the diagram, we have a picture of the reservoir routing effect on a "drought wave" in the input (Fig. 3B). Here a more representative time scale would be such that the duration of the "input drought" would be between several weeks and several months. With the aid of this diagram, some of the observations collected by Wilhite and Glantz (1985; also reprinted in this volume) are easily explained, and some pronouncements that seem contradictory become entirely logical.

Thus it becomes obvious why "meteorological droughts do not necessarily coincide with agricultural droughts" and why "hydrologic droughts are often out of phase with both meteorological and agricultural drought." Meteorological drought roughly coincides with precipitation shortage (i.e., with the "input drought" in Fig. 3B), while agricultural drought may be more closely related to the depletion of soil moisture storage (i.e., with, say, the drought in the output from the "small" reservoir system); and "hydrologic" drought defined on the basis of low streamflows may correspond to the drought in the output from our "large" reservoir system, which could represent the ground water storage supplying the "baseflow component" of streamflow. It is, of course, perfectly in order that all three "droughts" are out of phase with each other since the speed with which an input wave moves through a reservoir depends on the size of reservoir storage and on its release mechanism. Mathematically, the phase shifts can be traced to the aforementioned phase shift of a sine wave under integration. In addition to a phase shift, an input perturbation is attenuated in the course of passage through a storage; it emerges in the output in a smoothed-out form. Mathematically, this effect can be traced to the change of the delta function under integration. This smoothing effect explains the assessment of a recent Brazilian drought as a five-year drought according to policy makers and as only a two-year drought according to meteorologists, and a similar disagreement in 1984 between Australian meteorologists and agriculturists (Wilhite and Glantz, 1985; also reprinted in this volume). Obviously, meteorologists have based their assessment on precipitation corresponding to our "input drought," while the policy makers and agriculturists base their assessment on drought attenuated by storage in some type of hydrological reservoirs (e.g., on a drought related to soil moisture, ground water, or surface water storage).

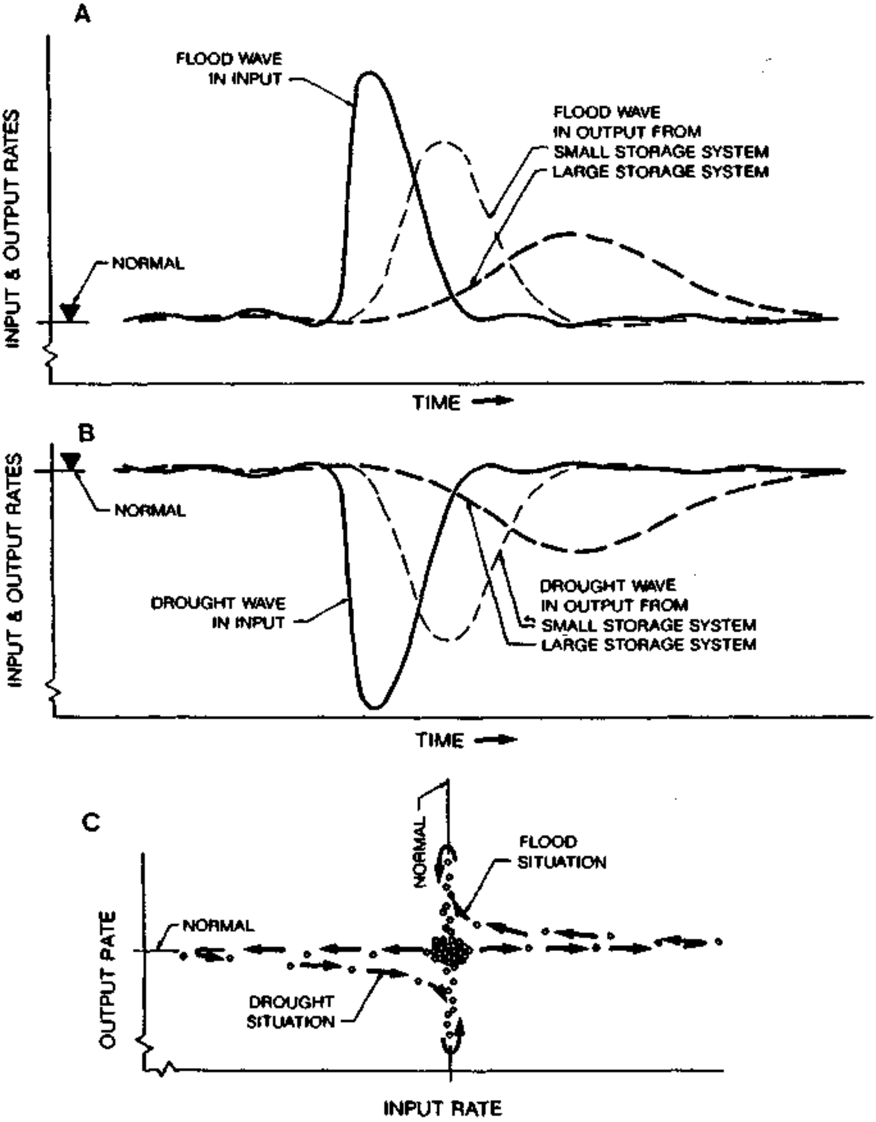

Fig. 3 Schematic representation of routing effect of a storage reservoir: A—"flood wave" routing; B—"drought wave" routing; C—input-output relationship for cases A and B.

A lack of appreciation of the difference between the precipitation process and the hydrological processes caused by a transformation of the former by a storage system has often led, on one hand, to the pursuit of correlations that do not exist and, on the other, to potentially erroneous reconstructions of ancient rainfall and drought patterns based on the assumption that such nonexistent correlations do exist. Examples of the first activity are the repeated attempts to find correlations between, for instance, ground-water levels and precipitation, or soil moisture and precipitation (e.g., Yu and Cruise, 1982). The inevitable findings that such correlations are poor or nonexistent are often presented as profound and unexpected discoveries and attributed to various exotic causes without ever mentioning the obvious reason--that there is no reason to expect a good correlation between a function and its integral (except in some special cases like the exponential function). This can be seen readily even by a cursory examination of the diagrams shown in Figs. 3A and 3B: high or low inputs may occur while the outputs are still more or less normal and the outputs may culminate long after the inputs have returned to normal. The resulting relationship between inputs and outputs then looks like the one shown in Fig. 3C. Not much imagination is needed to see that for a fluctuating input process and the corresponding output from a reservoir with an appreciable storage, the input-output correlation can be very low since the scatter of points on an input-output plot can be extremely high. From this it follows that reconstructions of past precipitation series--based on an assumption of their simple correlation with chronologies of lake deposits, tree rings, and so forth--can be misleading if the dynamics of the water-transfer mechanisms are not considered, since the latter processes may often more closely reflect fluctuations of large storage reservoirs like lakes and ground-water basins than fluctuations of their precipitation inputs.

Having illustrated the overall importance of storage for a proper understanding of the potential of hydrology for drought prediction, let's now return to the second most important aspect mentioned at the beginning of this section--the differences in the mechanisms that control inputs into and releases from the different types of hydrological storages.

Allowing for some simplification, we may say that inputs into and outputs from the surface water storage are dominated by mechanical and thermodynamical forces (gravity and friction controlling surface runoff and infiltration, radiation and heat transfer controlling evaporation); soil moisture movement is controlled by mechanical, thermodynamical, and electrochemical forces (infiltration, percolation, evapotranspiration, chemical bonding of water in the soil, water transport by plants); and ground-water movement is dominated by mechanical forces. Fluctuations of these forces have different rhythms, which may impose different frequencies and patterns on droughts exhibited by the different hydrological processes. It is difficult to speak about a "hydrological" drought in general since individual hydrologic processes have a wide spectrum of behaviors and because these processes may be combined in a wide variety of ways. Thus, the pattern of a streamflow record may be dominated by direct (surface) runoff, glacial melt, ground-water runoff (baseflow), evaporation, and so forth. For example, recently Fairbridge (1984) observed that the Nile River streamflow cannot be properly regarded as a result of one hydrological regime, but must be seen as a composite of two different regimes--the Blue Nile regime, dominated by the Ethiopian monsoons, high slopes, and moderate surface storage; and the White Nile, shaped by the precipitation on the equatorial plateau, the large storages of lakes Victoria, Kyoga, and Albert (Mobutu), and the enormous evaporation in the Sud region. These two regimes dominate the downstream flow in different seasons so that the regimes of spring and fall water shortages are quite different.

Another specific example of the differences in the regimes of different hydrological storages in the same river basin is shown in Fig. 4, reproduced from Klemeš (1983). The solid upper line shows the fluctuations of the total amount of liquid water stored in the basin; the dotted caps represent the accumulation of snow. It would be tempting to take the minima of this solid line as indicators of drought conditions in the basin and use them at least for a statistical prediction of drought frequencies, if not for real-time forecasting. The difficulty is that the line represents the sum of different types of storages whose relative proportions in the sum vary with time. A first step in trying to shed some light on the problem involved separating fluctuations of storage of gravity-controlled water from fluctuations of storage of "tension" water (mostly soil moisture). Although its accuracy is unknown, the result represented by the solid lower line (gravity-controlled storage) and the dashed line (tension storage) well illustrates the importance of such a differentiation for drought prediction. For example, it indicates that periods of soil moisture depletions—which often are the cause of an "agricultural"

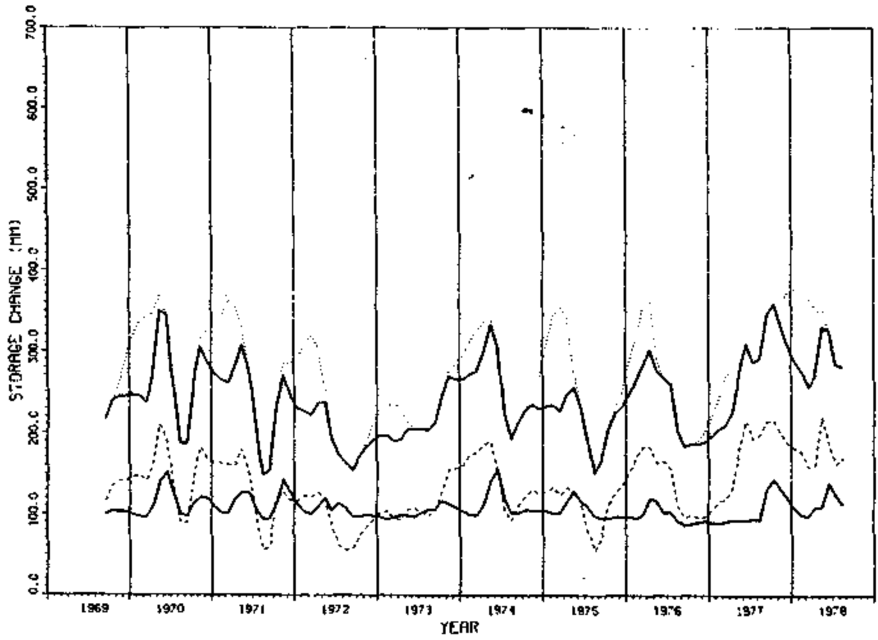

Fig. 4 Time series of storage fluctuations in Rainy Lake basin, Ontario, Canada: solid upper line = all liquid water; dotted segments = snow; solid lower line = gravity-controlled liquid water; dashed line = tension water (from Klemeš, 1983).

drought—tend to be shorter than periods of low ground-water levels, which may be indicative of "hydrological" droughts in terms of water supply shortages (drying up of wells, disappearance of springs, and so forth). Note, for example, that a longer drought is revealed in the solid lower line in 1976-77 than in the solid upper line, where the drought is obscured because of its partial compensation by abundant soil moisture.

To summarize, hydrology has a great potential for tracing the effects of meteorological droughts through the various hydrological subsystems and hence for real-time forecasting and statistical prediction of droughts or water shortages that affect users dependent on different sources of water supply.

CONCLUSIONS

It is beyond the scope of hydrology to offer an exhaustive analysis and complete understanding of the phenomenon of drought. Drought has many causes; hydrological causes are last among these. However, hydrology provides important insights, both into the effectiveness of methodologies used to analyze geophysical records for periodic or cyclic patterns to use in long-term drought forecasting and into the physical processes responsible for the modifications and transformations of the basic "drought signal" supplied by the precipitation record. These latter processes are of paramount importance to the short-; and medium-range forecasting of droughts that affect users dependent on different sources of water supply. In both cases, the value of the contribution of hydrology is directly proportional to the depth of insight into and understanding of the physical mechanisms controlling the various types of hydrological processes; it does not depend much on skill in fitting hydrological records with formal mathematical models aimed merely at preservation of various parameters and patterns of historic records. Unfortunately, present-day hydrology is dominated by the latter tendencies and, although the realization of their sterility is slowly increasing, much effort is needed to change hydrology's course to a direction in which its great potential can bear fruit.

REFERENCES

Fairbridge, R. W. 1984. The Nile floods as a global climatic/solar proxy. pp. 181-190. In N. A. Mornerand and W. Karlen,eds. Climatic Changes on a Yearly to Millennial Basis. D. Reidel, Dordrecht, Holland.

Feller, W. 1966. An Introduction to Probability Theory and Its Applications. 2nd ed., vol. 1. John Wiley and Sons, New York.

Klemeš, V. 1974. The Hurst phenomenon: A puzzle? Water Resour. Res. 10, no. 4 (August):675-688.

Klemeš, V. 1978. Physically based stochastic hydrologic analysis. Adv. Hydroscience 11:285-356.

Klemeš, V. 1982a. Empirical and causal models in hydrology. pp. 95-104. In Scientific Basis of Water-Resource Management. National Academy Press, Washington, DC.

Klemeš, V. 1982b. The essence of mathematical models of reservoir storage. Can. J. Civil Eng. 9, no. 4:624-635.

Klemeš, V. 1983. Conceptualization and scale in hydrology. J. Hydrol. 65:1-23.

*) Klemeš, V.; and I. Klemeš. 1987. Variations on the themes of Slutzky, Hurst and Yule. National Hydrology Research Institute, Environment Canada, Saskatoon, Saskatchewan (submitted for publication).

Neville, A. M.; and J. B. Kennedy. 1964. Basic Statistical Methods for Engineers and Scientists. International Textbook Company, Scranton, PA.

Slutzky, E. 1927. The summation of random causes as the source of cyclic processes. (In Russian). Problems of Economic Conditions 3, no. 1 (reprinted in English in an expanded form, 1937, in Econometrica 5:105-146).

Wilhite, D. A.; and M. H. Glantz. 1985. Understanding the drought phenomenon: The role of definitions. Water International 10:111-120.

Yu, S. L.; and J. F. Cruise. 1982. Time series analysis of soil moisture data. pp. 600-606. In A. H. El-Shaarawi and S. R. Esterby, eds. Time Series Methods in Hydrosciences. Elsevier, Amsterdam.

*) See K+K, WRR, 24, 1, 94-104, 1988