NOTE ON THE ASSUMPTION OF HYDROLOGIC STATIONARITY

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ABSTRACT

Recent arguments that empirical evidence points to hydrologic nonstationarity that is a consequence of climate change cannot be dismissed. Yet the operational assumption of hydrologic stationarity used extensively in water management should not be discarded without further study. It remains to be determined if assumed forms of hydrologic nonstationarity would tax the ability of water systems, through their robustness and resilience, to absorb the additional stresses that would follow from those assumptions. One approach to making the determination is by way of an assessment of the expected economic regret in water management resulting from the use of the assumption of restrictive hydrologic stationarity in the face of perceived hydrologic trends.

INTRODUCTION

Hydrology is a manifestation of climate, and hydrology's large spatial and temporal patterns are shaped by geology and biology. The low frequency characteristics of the patterns are generally described in terms of the hydrologic cycle and the global water balance. Matalas et al. (1982) suggested that the hydrologic cycle should be viewed as driven not just by physical forces, but also by human activity entailing impacts on water quality as well as water quantity. Van Hylckama (1970) noted that there is considerable seasonal variation in the global water balance. He estimated that 6,000 km^3 more water is stored on the land in March than in September, 6,000 km^3 more water is stored in the ocean basins in October than in March, and 600 km^3 more water is stored in the atmosphere in September than in March. Two points are noted about the global water balance. First, the seasonal variation is of the same order of magnitude as the resource countable runoff of 9,000 km^3 estimated by Ambroggi (1980), and second, Munk and MacDonald (1975) calculated that the seasonal variation in the global water balance exerts a small but nonnegligible effect upon the wobble of the Earth as the Earth rotates around the Sun.

A large scale hydrologic perspective is relevant to today's discussions of the impact of climate change on hydrology at smaller spatial scales. In the absence of detailed knowledge of the driving forces of the hydrologic cycle and the seasonal variation in the global water balance, it is difficult to assess the unfolding of hydrologic changes at spatial and temporal scales of practical interest in response to climate change. The assessment poses a number of challenges, among which are the following. 1) It is important that the global water balance and its seasonal variation be defined at a spatial resolution commensurate with the smallest spatial scale of seasonal climatic variation defined by global circulation models. 2) An account should be taken of the impact of human activity, most notably changes in land use, on hydrology up to at least the regional scale, and this account should be weighed against climate induced hydrologic change. 3) If human activity perturbs the hydrologic cycle and the global water balance to a nonnegligible degree, then an account of the impact of climate change on water quality should be taken, an account much fuller than that presently available. (See, e.g., Jacoby 1990). 4) And the impact of hydrologic change in quantity and quality on water management, as translated from climate change and human activity, should be assessed in relation to the buffering capacity of water resource systems. The buffering capacities of the systems temper the scientific shortcomings of operational assumptions on which the systems are managed.

The last challenge, in reference to one basic operational assumption, namely, that of a stationary hydrology, is discussed below.

HYDROLOGIC UNCERTAINTY

Among the uncertainties affecting the management of water resource systems are those that derive from the lack of knowledge as to how hydrology will unfold in the

future, more specifically over the time bound by the economic time horizon. Interest in the hydrologic past is driven in expectation of shedding light on the hydrologic future.

On a geologic scale there is little argument that hydrology has unfolded as a transient process in response to changes in climate. Over long periods of time encompassing glacial epochs and tectonic and volcanic events, resulting geomorphologic changes argue against a steady state hydrology. However, over historical time, it is not clear that the changes in hydrology can be attributed strictly to changes in climate. Hydrologic changes may be a consequence of human activity. Herein, the term human activity refers to the more traditional modes of effecting hydrologic change, e.g., changes in land use, impoundment of waters, and divergence of river courses. Changes in hydrology that are consequent to the changes in climate that derive from the increasing content of CO_2 in the atmosphere due to the combustion of fossil fuels and the clearing of forests and other lands for agriculture are also changes affected by human activity. This activity is taken as separate from the more traditional modes of effecting hydrologic change. The differentiation of human activities having the potential to affect hydrologic change allows for distinguishing between policies for mitigating adverse economic and social impacts resulting from hydrologic change. The differentiation of the human activities is blurred, and as a consequence there is an added element of uncertainty in formulating policies to offset economic and social losses brought about by hydrologic change.

For hydrologic changes to be due solely to non-climatic factors, climate must be a steady state process. A steady state hydrology, at least over the short run, may be the consequence of counteracting changes induced by various factors. Relative to water management, the issue is whether the hydrology that will unfold over some economic time horizon will do so in a manner such that the hydrology will be reflected as the output of a system in a steady or a transitory state.

The hydrologic inputs to water management are assumed to be realizations of stochastic processes. That assumption tacitly implies that the generating mechanism of hydrology is governed by a probability law and it is this law that gives meaning to the assumption that the hydrologic process is stationary or otherwise. In the absence of the law, itself an assumption, the question whether hydrologic processes are stationary or not is moot. However, the question remains if hydrology is changing in response to changes in climate or to changes in other hydrologically regulating variables. The law may be interpreted as an aspect of knowledge, an interpretation that many find more acceptable than that of the law being an aspect of external reality. Either interpretation allows for the rich and powerful theories of probability and statistics to provide a substitute for the uncertainties entailed in managing water resource systems. The added assumption that the law covers hydrology as a stationary process simplifies the task of managing water systems in an economically efficient and effective manner – simplifies in the sense that fewer additional assumptions need be made about the hydrologic future. However, the simplicity afforded by the assumption of stationarity does not assure the achievement of optimal efficiency or effectiveness in system management.

Stationarity implies that the future will be statistically indistinguishable from the past. Operationally, the notion of stationarity is qualified. Strict stationarity implies that the probability law that governed the past will govern the future. A less restrictive form of stationarity allows for the probability law to change with time, but in a manner that does not affect specific statistical characteristics, e.g., the lower order moments or the degree of importance of the absolute times of events over that of specific lags in the time of events. All other statistical properties may change with time, whereby those statistical properties may be nonstationary.

In water management a restricted form of stationarity is assumed. Hydrologic processes are assumed to be weakly stationary, such that the covariances of events separated in time depend only on the time differences and not on the absolute times of the events. Also, it is assumed that the processes are stationary up to at least the third moment and perhaps the fourth moment, such that the mean, variance, skewness, and perhaps the kurtosis of the past will be those of the future. It is further assumed, at least implicitly, that if any of the other statistical characteristics of the probability law are nonstationary, those nonstationarities will have no impact on the management of water resource systems. When a particular probability distribution is specified, stationarity holds for all moments that exist (are defined) for that distribution. It is assumed at least implicitly that the stationarities in the statistical characteristics, say the higher order moments, that cannot be confidently estimated have no effects on the management of water systems.

The implicit assumptions that the stationarities or nonstationarities in the higher order moments have no

effects on the management of water resource systems are to a considerable extent reasonable. Design techniques, operating rules, and management procedures and criteria have been advanced as functions of the lower order moments. Departures from expected system performances have traditionally been ascribed to the sampling errors and the choice of probability law pertaining to the hydrologic inputs as well as to the economic and other inputs. It can be argued that the departures from expected system performances are dominated by nonhydrologic inputs (see, e.g., James *et al.,* 1969).

Current interests in climate change have focused attention on consequent potential hydrologic change and thereby the questioning of hydrologic stationarity. There seems to be a general consensus that empirical evidence points to hydrologic nonstationarity and that the nonstationarity derives from climate change, more specifically to global warming. That evidence cannot be dismissed. By the same token the utility of the assumption of hydrologic stationarity should not be discarded, at least not until the nonstationarity implied by the empirical evidence has been translated into operational terms of water management. To make that translation, several questions need to be answered. For example, does the evidence point to nonstationarity in the mean alone or does it point to nonstationarity in other of the low order moments as well? How strong is the evidence? For evidence predicated on confidence levels, the choices of levels should be rationalized. If the evidence is derived from a collection of hydrologic series, is the confidence level at which change is statistically significant that for which the covariance of the collection is taken into account?

Answers to statistical questions of these sorts must contend with the well-known difficulties of differentiating between real and perceived trends and differentiating between a trend and a segment of an oscillatory movement. The question whether hydrology is a short or long memory process, a central question during the early 1950s through the 1970s, remains relevant to the discussions of climate-induced hydrologic change. The relevance relates to the assumption of weak STATIONARITY and the fact that short realizations are more likely to evidence "trends" if the realizations pertain to long rather than short memory processes.

There are still more questions to be addressed. Does the evidence suggest that nonstationarity is due to climate change entirely? A satisfactory answer to that question is important. Policies adopted to cope with hydrologic nonstationarity induced by climate change would not likely be the same as those adopted if the nonstationarity derives from changes in land use or through some other means. Do water systems have sufficient buffering capacity to absorb hydrologic change? Allied to this question is another – does the evidence suggest that the magnitudes of the changes in statistical descriptors of hydrology that are likely to occur over the next several decades are within the range of sampling errors of those descriptors conditioned on the assumption of appropriate restrictive stationarity? These last two questions are examined briefly.

Matalas and Fiering (1977) noted that large water resource systems have a high degree of redundancy and robustness that enables them to adapt technologically and institutionally to severe stresses. There is amply empirical evidence of systems having been operated under short-run emergency situations of droughts and floods in manners enabling communities to adapt successfully. The systems have been designed and operated on statistical estimates of the parameters and not on the parameter (population) values themselves. Some of the stresses imposed on the systems derive from statistical sampling errors under stationary conditions. It may be that other stresses relate to hydrologic changes due to undetected climate shifts. Systems are to varying degrees robust, i.e., they are to, varying degrees, insensitive to errors random (e.g., statistical sampling errors) or otherwise (e.g., computational errors, in design). To varying degrees a system is resilient, i.e., it can be operated technologically or institutionally to simulate over the short run a system of another design such as to limit economic losses. The greater the degree of robustness and of resilience, the greater is the operational merit of the assumption of stationarity.

The ability of systems to absorb stresses, i.e., to be technologically and institutionally operated over the short run as though the systems conformed to alternate optimal designs, indicates that the design and operation of systems need not be immediately modified to face the threat of climate change. There is time to muddle through with current practice, to adopt a wait-and-see policy, and to follow one's gut feelings, all of which are rational acts of decisionmaking under uncertainty.

HYDROLOGIC METRIC

Answering many of the questions posed above in a highly satisfying manner would be greatly enhanced by developing hydrologic metrics at various spatial scales. One metric is provided by the global water balance in

relation to continental runoff. The purpose of the metric is to provide a basis to ascertain the consistency in the finding of various hydrologic studies dealing with large regional scales. For example, is nonstationarity evidenced in one region consistent with that evidenced in another region and does the evidence translate into a global setting?

A basis for developing a large (continental) scale metric is provided by the work of the U.S.S.R. National Committee for the International Hydrological Decade carried out through the auspices of UNESCO and reported on in 1974 (English translation in 1978). The Committee presented estimates of runoff for the period 1918 through 1967 for the continents of Africa, Asia, Australia (including Oceania), Europe, North America, and South America. Estimates of global runoff are given by the sequence of contemporaneous continental runoffs. The seven runoff sequences for the common 50-year period were examined for simple linear trends over time. Linear trend was determined by simple regression of runoff on time (year). The continental trends of the normalized flows are depicted in Figures 1 through 3, where the normalized flows are simply the departures of the flows from their respective continental means standardized by their respective continental standard deviations. The global trend of the normalized flows is depicted in Figure 4, where the global normalized flows were defined analogously to the normalized continental flows.

The regression coefficients measuring linear trends vary from -0.0084 for Asia to 0.0228 for Australia and Oceania. The trends are not statistically significant at the more-or-less conventional probability levels except for the positive trend for North America that is significant at about the 95% level and the positive trend for Australia and Oceania that is significant at about the 99% level. The positive global trend is not significant. It would be interesting to see if these trends would prove to be consistent with those for collections runoff records on specific continents covering the common period of 1918-1967. The assessment would be more interesting if the estimates of continental and global runoff covered the period 1918 to present.

It is noted that one feature of runoff is common to all the continents and to the continents collectively, namely, that in the neighborhood of 1940, runoff was low. This feature is particularly striking for the North America and the Australian and Oceanic runoffs and for the Global runoff. The feature is highlighted by forming the time series of the cumulative sums of the normalized flows. The troughs of the cumulative sums of the normalized runoffs are shifted slightly forward in time. See Figures 5 through 8. These graphs appear in the cited work of the U.S.S.R. Committee to the International Hydrological Decade where they are given brief climatic interpretations.

Forming the time series of the cumulative sums of the normalized runoffs is recognized as a step toward performing R/S analyses to determine the Hurst coefficient (Hurst 1951) as a means of discerning if the series are best considered as realizations of short or long memory processes (Mandelbrot and Wallis 1969). If these time series of continental and global runoff are regarded as realizations of long memory processes, then the trend analyses must be examined more closely. The well-known pitfalls in differentiating between real and perceived trends are compounded in the presence of long term memory.

Attention is drawn to this feature because it is revealed in the levels of closed lakes in the western United States. For the elevations of Devils Lake near Devils Lake, North Dakota and the Great Salt Lake near Salt Lake City, Utah, the feature is noted in Figures 9a and 9b. In reference to the elevations of Devils Lakes, there are questions to explanations of the feature in strictly climatic terms (William Werick, U.S. Army Corps of Engineers:

Personal Communication 1997). Over the period 1918-1967, the minimum elevation for Devils Lake occurred in 1940 and that for Great Salt Lake in 1964. In reference to the cumulative sums of normalized elevations, the "global" minimum value for Devils Lake attained in 1949 and that for Great Salt Lake attained in 1964. In 1940, a "local minimum" occurred for Great Salt Lake.

These statistics should be viewed cautiously. No account was taken of serial correlation, no assessment was offered about stochastic memory, and the "chosen" levels of statistical confidence were not rationalized. The point being made is that long records of continental runoff would provide a basis by which regional trend studies could be assessed for consistency in relation to continental and global scale hydrologies. The statistical results noted above would bear closer scrutiny if the data were more current. Updating the runoff records is in the interest of scientific hydrology and the update would be useful in addressing questions about the assumption of stationarity in operational hydrology and perhaps it would strengthen arguments that attribute climatic significance to hydrologic anomalies.

POSTSCRIPT

As a stochastic process within the broad flow of time, hydrology is a nonstationary process. Today's rivers are not those of yesterday. Erosional processes have obliterated traces of many ancient stream courses, but some may still be seen, e.g., on the ocean floor in the Sunda Banda region of Indonesia. Over the short run, both past and future, hydrology does not reveal itself as a clear nonstationary process. In the context of water management, the operational assumption of hydrologic stationarity has been accepted on the grounds that historical records do not exhibit strong indications of nonstationarity and the assumption simplifies the task of managing systems in an economically efficient and effective manner. The simplicity follows from the fact that fewer assumptions need be made as to how hydrology will unfold in the future. Simplicity, however, is not enough to warrant the making of the assumption of stationarity. The merit of the assumption follows from the fact that a restrictive form of stationarity is assumed, one that is not obviously at variance with empirical assessments of the stochastic structure of historical records and the fact that the restrictive form of the assumptions allows for the theories of probability and statistics to be drawn upon extensively in developing optimal designs of water systems.

With attention focused on the potential of hydrologic impacts of climate change, the assumption of hydrologic stationary has been questioned. There is an increasing consensus that current changes that are occurring in climate are being reflected in hydrologic records, and that the reflection calls into question the assumption of stationarity. It is unclear, however, if the perceived trends in hydrologic records are such that over the next 50 to 100 years the changes in the estimates of the low order moments that characterize hydrologic sequences will or will not be bound by the sampling errors predicated on the assumption of stationarity. Claiming nonstationarity is not enough. It must be shown that the perceived nonstationarity is real enough and has a significant effect on the management of water systems.

The robustness and resilience of large water systems buffer the system against stresses by allowing the system to be operated technologically and institutionally as to limit economic losses. The buffering capacity afforded by the attributes of robustness and resilience enables a system to absorb, so to speak, sampling errors associated with the estimates of the statistical parameters upon which the design of the system is based. If perceived trends are to be accepted as real trends then it must be shown that the stresses placed on the system as a consequence of the assumption of restrictive stationarity tax the system's buffering capacity. Studies of the sensitivity of water systems to climate change have not kept pace with hydrologic studies seeking evidence of climate change in historical hydrologic records and quantifying the climatic forcings of hydrology. What are the expected economic regrets in water management resulting from the use of the assumption of restrictive hydrologic stationarity in the face of perceived trends?

Hydrologic studies, climate motivated or otherwise, would benefit by the development of hydrologic metrics at various spatial scales. A developmental step was provided by the work of the U.S.S.R. National Committee for the International Hydrological Decade under the auspices of UNESCO. An update of that work to make current the estimates of continental and global runoff would provide a useful metric to assess the consistencies of hydrologic studies at various regional scales. The water balance is fundamental to hydrologic study.

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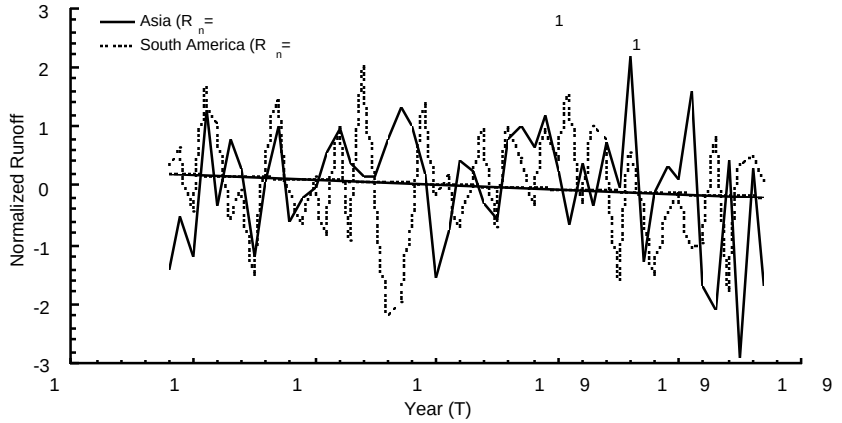

Figure 1: Time Series of Continental Runoff — Asia and South America

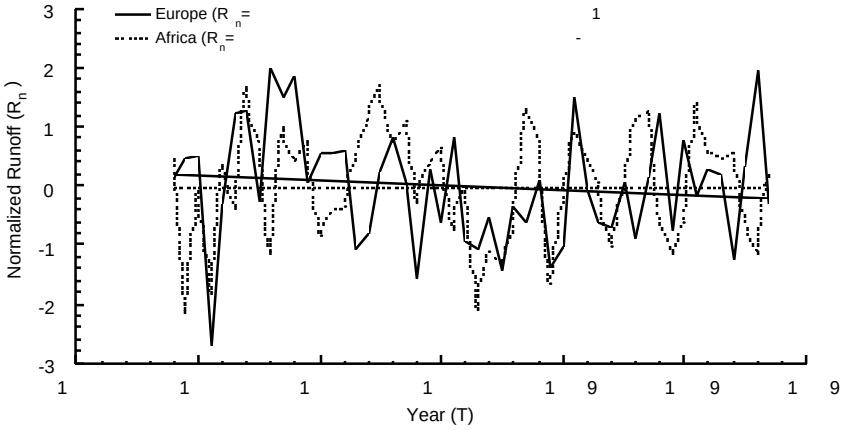

Figure 2: Time Series of Continental Runoff — Europe and Africa

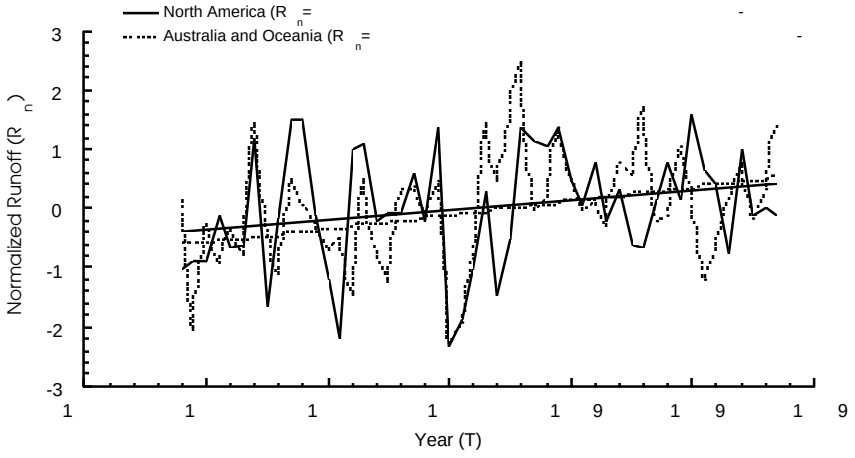

Figure 3: Time Series of Continental Runoff — North America and Australia and Oceania

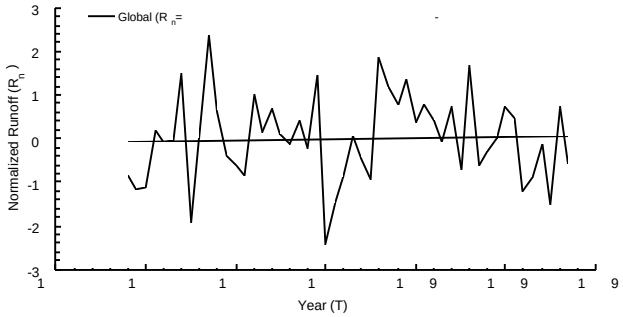

Figure 4: Time Series of Continental Runoff — Global

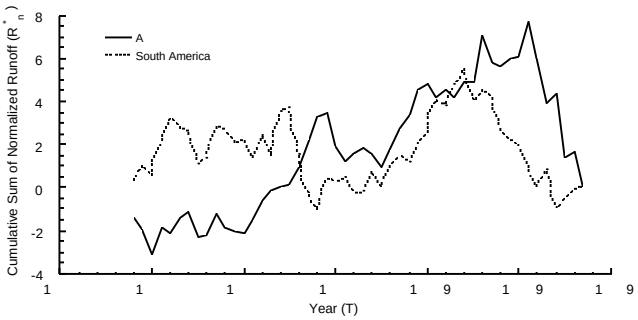

Figure 5: Time Series of Cumulative Sum of Normalized Runoff — Asia and South America

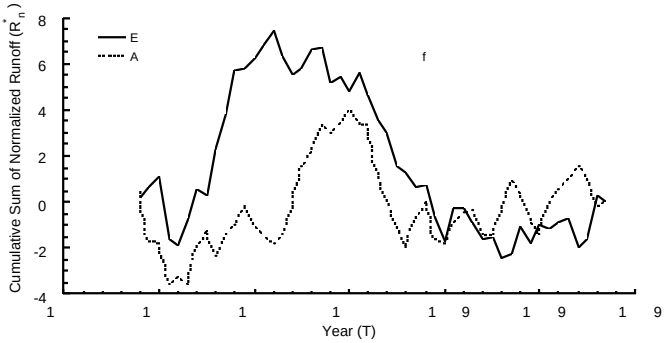

Figure 6: Time Series of Cumulative Sum of Normalized Continental Runoff — Europe and Africa

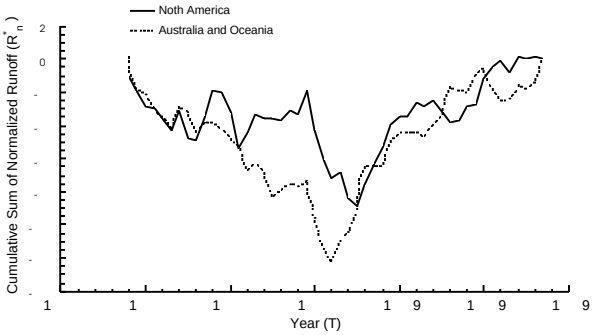

Figure 7: Time Series of Cumulative Sums of Normalized Continental Runoff — North America and Australia and Oceania

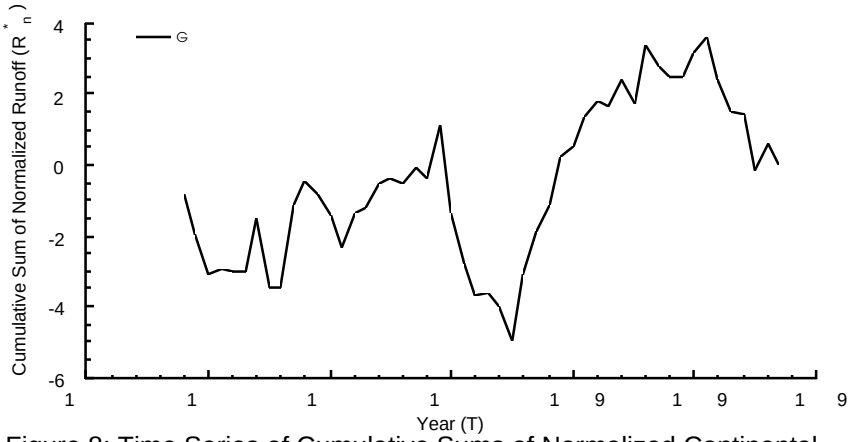

Figure 8: Time Series of Cumulative Sums of Normalized Continental Runoff — Global

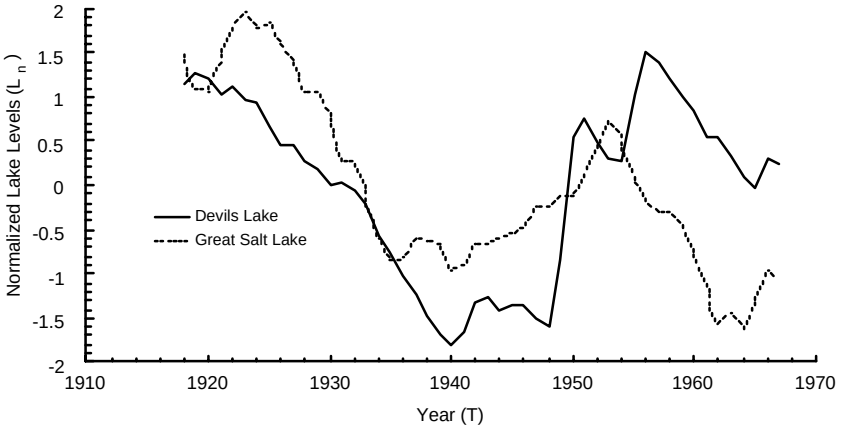

Figure 9a: Time Series of Normalized Lake Levels for the Period 1918-1967 — Devils Lake and Great Salt Lake

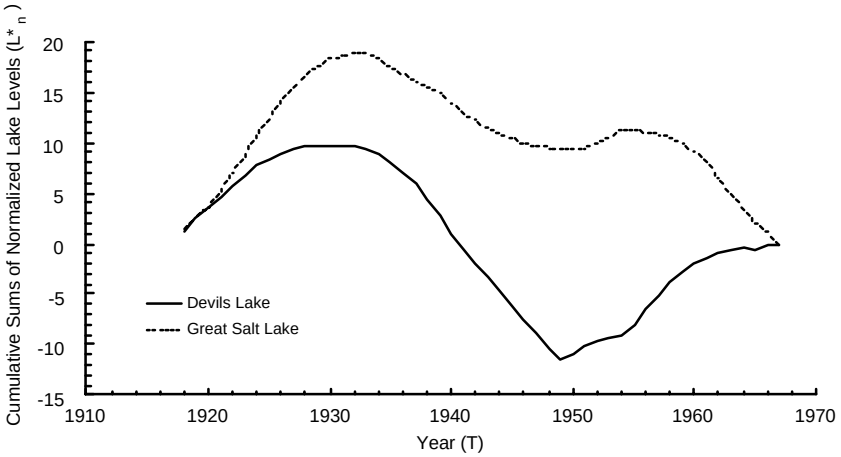

Figure 9b: Time Series of Cumulative Sums of Normalized Lake Levels for the Period 1918-1967 — Devils Lake and Great Salt Lake