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HYDROLOGIC SCENARIOS FOR SEVERE SUSTAINED DROUGHT IN THE SOUTHWESTERN UNITED STATES[1]

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ABSTRACT: This paper considers the risk of drought and develops drought scenarios for use in the study of severe sustained drought in the Southwestern United States. The focus is on the Colorado River Basin and regions to which Colorado River water is exported, especially southern California, which depends on water from the Colorado River. Drought scenarios are developed using estimates of unimpaired historic streamflow as well as reconstructions of streamflow based on tree ring widths. Drought scenarios in the Colorado River Basin are defined on the basis of annual flow at Lees Ferry. The risk, in terms of return period, of the drought scenarios developed, is assessed using stochastic models.
(KEY TERMS: drought; streamflow; Colorado River; hydrology; water resources management.)

INTRODUCTION

The inherent scarcity of water in the semi-arid to arid regions of the southwestern United States (Figure 1) is exacerbated by the occurrence of frequent and persistent droughts (Stockton *et al.*, 1991). The impact of these droughts is constantly changing as the growing population places increased demands on supplies. This is countered by the development of storage and distribution systems that can store water for up to decades and transport water thousands of miles. These measures provide security against local shortages of short duration but effectively interlink large regions. However, these large interlinked storage and distribution systems are now susceptible to sustained regional shortages of water supply.

This paper summarizes the hydrology work done as part of a multi-disciplinary study to assess the likely impacts of severe sustained drought in the region served by the Colorado River. It is a precis of the key results presented at greater length by Tarboton (1994). Figure 1 is a schematic of the study area. Most of the streamflow in the Colorado River comes from snowmelt in the Rocky Mountains in Colorado, Utah, and Wyoming. Several reservoirs, the largest of which are Lake Powell and Lake Mead, provide storage, hydroelectric power, and flood control. The use of water from the Colorado River is strictly controlled and governed by a complex system of law centered on the Colorado River compact. This apportions use of water between the upper and lower basins of the Colorado River basin. Use of water is apportioned among states by other compacts and court decrees. Some of the water supply systems for utilization of this water are indicated in Figure 1. Southern California – in particular the metropolitan area surrounding Los Angeles – draws water from the Colorado River via the Colorado River aqueduct, as well as from northern California. This paper focuses only on streamflow in the Colorado River. For drought impacts on southern California, the possibility of simultaneous shortage in the Colorado River and northern California is considered by Tarboton (1994).

In this paper critical periods of shortage in the historic and paleo (tree ring) streamflow record are identified. These are used to develop study scenarios. Stochastic techniques were used to characterize the spatial distribution of supply during these scenarios and to assess the risk or likelihood of occurrence of these scenarios.

The sources of data upon which this paper was based consisted of the following unimpaired streamflow estimates and streamflow reconstructed from the measurement of tree-ring widths:

1. Historic unimpaired streamflow at 29 sites in the Colorado River basin, 1906-1983 (78 years), as estimated by the U.S. Bureau of Reclamation.

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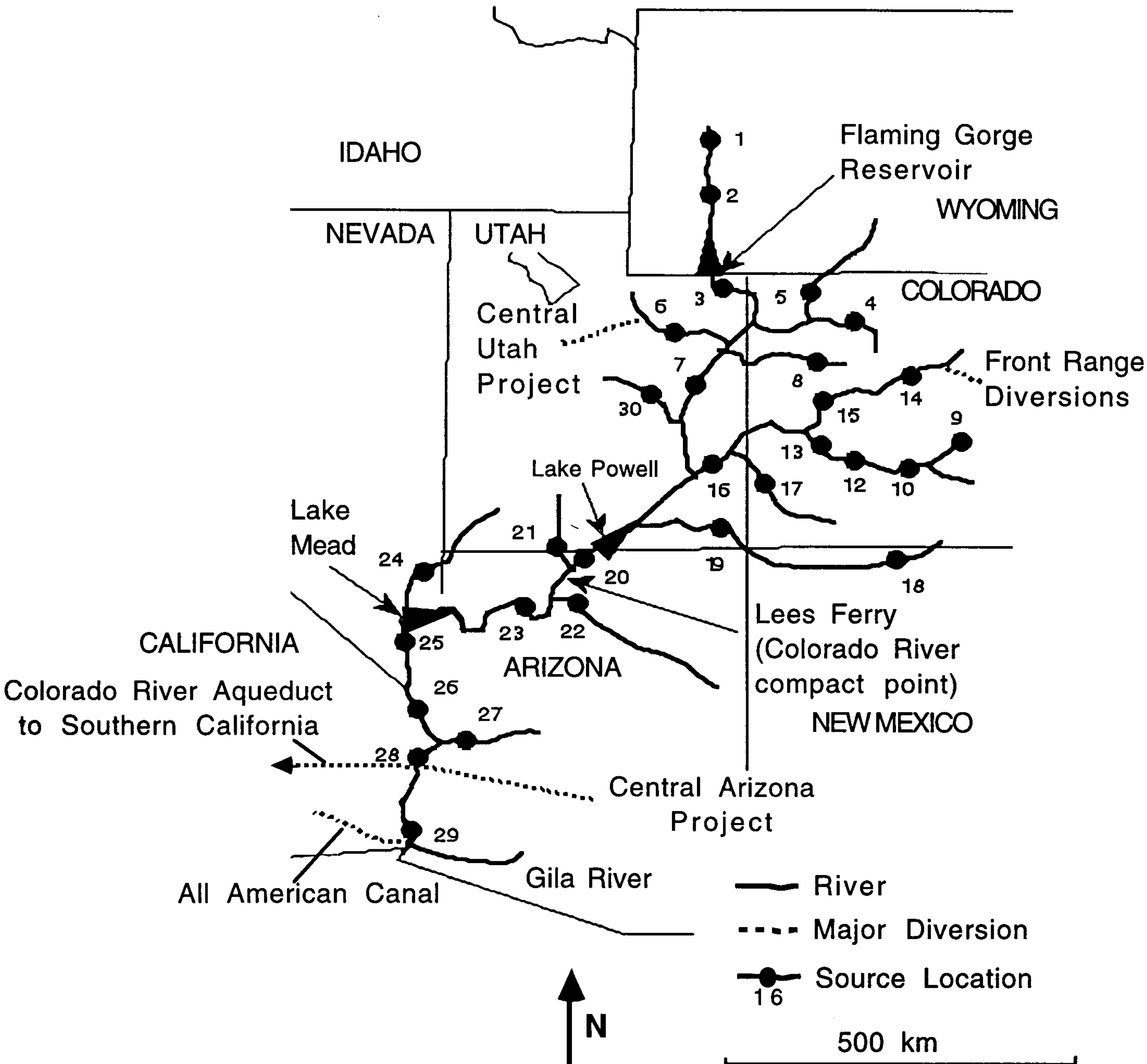

Figure 1. Southwestern United States Study Area Showing the River and Water Distribution Systems Involved. Numbered points are the source inflow locations used by the Colorado River simulation model.

2. Tree-ring reconstructed streamflow at Lees Ferry on the Colorado River, 1520-1961 (442 years), from Stockton and Jacoby (1976).

3. Tree-ring reconstructed streamflow at Lees Ferry on the Colorado River, 1568-1962 (395 years), from Michaelson *et al.* (1990).

Streamflow at Lees Ferry is used in this paper to refer to streamflow at the Colorado River compact point near Lees Ferry, Arizona, defined as a point one mile downstream of the confluence of the Colorado and Paria Rivers. This is the sum of streamflow measured at the Lees Ferry gage upstream of the Paria confluence and the Paria gage. The compact point legally subdivides the Colorado River basin into upper and lower basins.

Unimpaired streamflow is measured streamflow adjusted for anthropogenic consumptive use and reservoir operations. It is an estimate of what streamflow would have been had the basins remained in their natural state.

Tree-ring studies offer a physical basis for the extension of hydrologic records further back than observed records, and thus they provide a window into the past that may yield additional information on the possible magnitude and frequency of the occurrence of droughts. These record extensions do not suffer from the uncertainty associated with stochastically generated sequences, but they do contain uncertainty associated with the relationship between tree ring widths and streamflows. Despite these drawbacks, tree rings often provide the only physically realistic glimpse of past hydrologic conditions which could recur and should be planned for. The approach in this work was to take advantage of the information provided by tree-ring reconstructions of streamflow to identify and develop severe drought scenarios. To allay skepticism regarding the use of tree ring reconstructed streamflow, one drought scenario based only on recorded streamflow was used.

Figures 2, 3, and 4 compare observed and tree-ring reconstructions of streamflow in the Colorado River at Lees Ferry. The Colorado River streamflow reconstructions are regarded in the tree-ring literature as adequate (Michaelson *et al.*, 1990; Stockton and Jacoby, 1976). The cross correlation (see, for example, Benjamin and Cornell, 1970, p. 15, Equation 1.3.2) between observed and reconstructed streamflow is 0.76 for the Stockton and Jacoby reconstruction and 0.77 for the Michaelson *et al.*, reconstruction. Table 1 gives statistics of the observed and reconstructed streamflow series. Notice that since the reconstructed streamflow is obtained from regression of tree ring width indices against the observed streamflow, the unexplained variance is omitted, resulting in smaller standard deviations in the reconstructed as compared to observed streamflow.

One feature of the Lees Ferry reconstruction is an apparent difference in the mean over the period of recorded flows (15.2 million acre-feet, MAF) from that of the reconstructed flows (13.5 MAF) (see Figure 3). [The units used for streamflow are either million acre-feet (MAF) per year or thousand acre-feet (KAF) per year; 1 acre-foot is 1.23 x 10^3 m^3.] A t test indicates that this difference is significant ($t > 3$, $p < 0.004$). This apparent nonstationarity is of concern because the methods for reconstruction of streamflow from tree-ring indices include detrending (removing nonstationarity) from tree-ring indices before correlation with streamflow. This feature is apparent in both Lees Ferry reconstructions.

The differences between the two Colorado River reconstructions are disturbing and could have a significant impact on planning strategies. The ten-year moving averages (Figure 4) sometimes differ by as much as 2 MAF between the two reconstructions when compared to a mean of 13.5 MAF. This occurs immediately after a sustained severe drought from 1600 to 1630 and could be important for recovery of the system. It also occurs from 1800 to 1830 where one reconstruction is in a drought and the other in surplus. However, differences such as these are

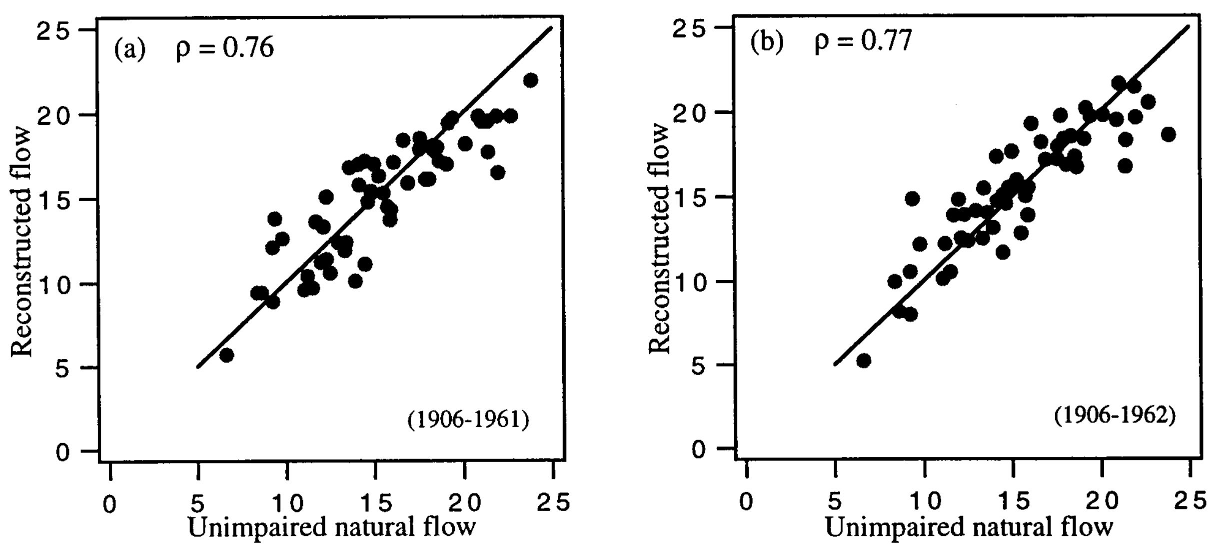

Figure 2. Comparison of Observed and Tree-Ring Reconstructed Annual Streamflow in Million Acre Feet (MAF): (a) Lees Ferry Reconstruction (Stockton and Jacoby, 1976); (b) Lees Ferry Reconstruction (Michaelson *et al.*, 1990). The solid line is a 1:1 line and ρ indicates cross correlation coefficient.

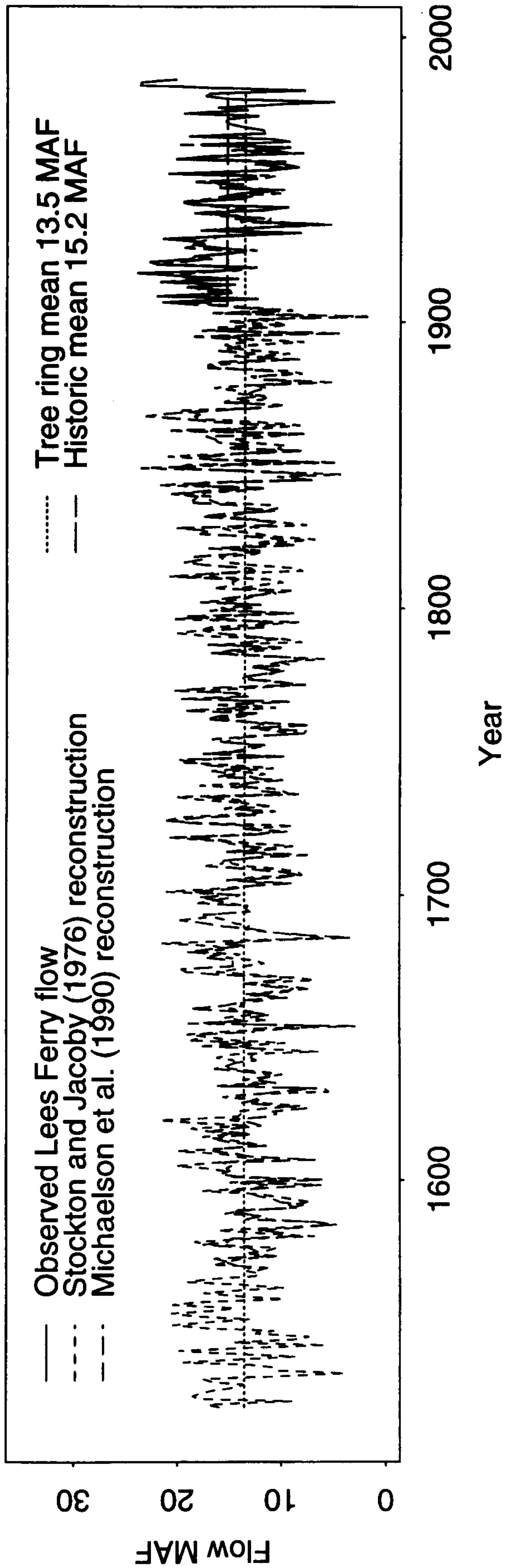

Figure 3. Time Series of Historic and Reconstructed Streamflow at Lees Ferry.

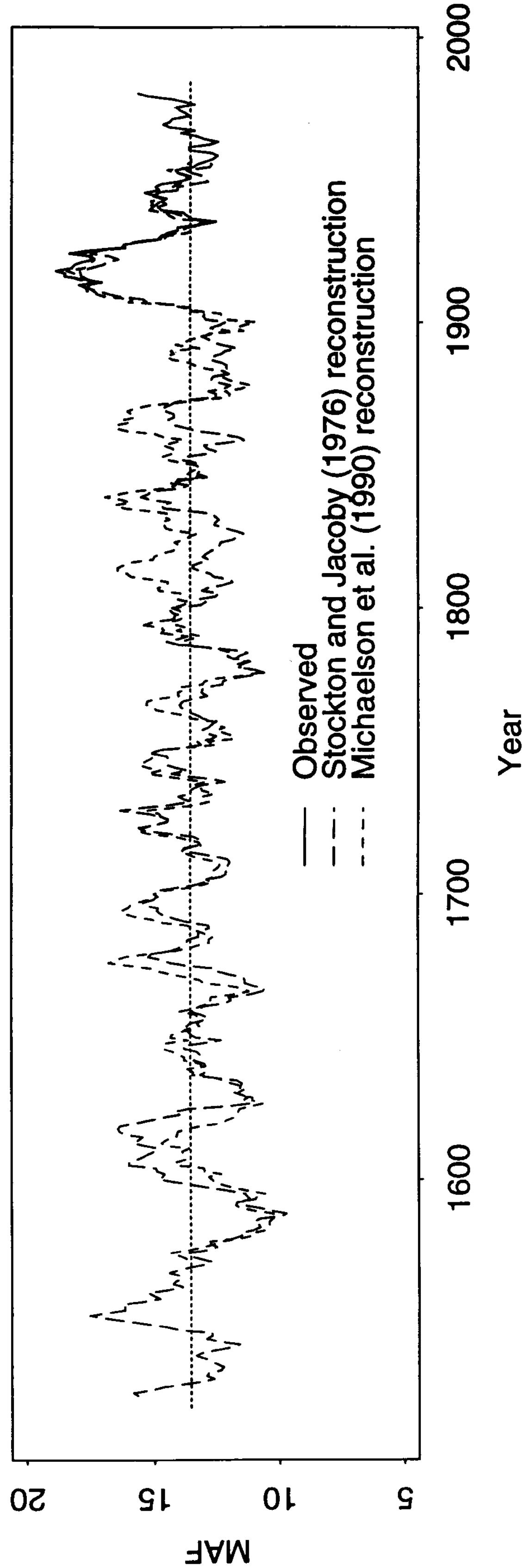

Figure 4. Ten-Year Moving Average of Historic and Reconstructed Streamflow at Lees Ferry.

TABLE 1. Statistics of Streamflow Series.

Series	Length (years)	Mean (MAF)*	Standard Deviation (MAF)	Annual Lag 1 Correlation	Hurst Coefficient
Unimpaired Flows at Lees Ferry 1906 to 1985	80	15.2	4.24	0.21**	0.73
Stockton and Jacoby (1976) Lees Ferry Reconstruction	442	13.5	3.59	0.32	0.63
Michaelson *et al.* (1991), Lees Ferry Reconstruction	395	13.8	3.61	0.26	0.65

*MAF (million acre-feet) = acre feet x 10^6 = 1.2^3 x 10.9 m^3.
**This correlation is not statistically different from 0 at the 95 percent confidence level.

reportedly typical statistical discrepancies in these type of tree-ring studies (Loaiciga *et al.*, 1992; Loaiciga *et al.*, 1993).

In the remainder of this article we used the Stockton and Jacoby (1976) reconstruction, for reasons detailed in Tarboton (1994).

IDENTIFICATION OF DROUGHTS AND DROUGHT SCENARIOS

Several options are available for the identification of severe sustained droughts in a flow record. Some of these are:

1. The drought with the maximum deficit magnitude (largest accumulated deficit below the mean annual flow over a continuous period with flow below the mean).
2. The drought that would cause the greatest reservoir depletion in a storage deficit analysis with fixed demand.
3. Visual inspection.

Figure 5 illustrates the application of these procedures to streamflow in the Colorado River at Lees Ferry. In the first option a drought is defined as a consecutive series of years during which the average annual streamflow is continuously below some specified threshold level, which is typically taken to be the long term mean (Dracup *et al.*, 1980; Yevjevich, 1967; Kendall and Dracup, 1991a). These periods are termed hydrologic droughts. A hydrologic drought can be defined by the following three attributes: (1) duration (L); (2) deficit magnitude (M) (the cumulative deficit below the threshold); and (3) deficit intensity [the average deficit below the threshold (M/L)]. A drawback of this procedure is that it classifies separately droughts that occur in quick succession separated by a single wet year (greater than the mean flow) that is insufficient to fill reservoirs.

Option (2), storage deficit analysis [also referred to as the sequent peak procedure (Kendall and Dracup, 1991b)] is a procedure whereby the storage deficit in a hypothetical semi-infinite reservoir initially full (zero deficit) is computed. Change in deficit is calculated each year by using a constant yield (taken to include outflow as well as evaporation) minus the inflow. If the deficit ever becomes negative, the excess is assumed to spill and deficit is reduced to zero. The maximum deficit is the storage capacity theoretically required to support the specified outflow or yield. In Figure 5d the yield was taken as 98 percent of the mean annual reconstructed streamflow (13.26 MAF), to reflect a high level of development. This high utilization is what is projected for the Colorado River in the year 2020 and is best for identification of sustained critical periods. An advantage of this analysis is that it gives an idea of the time required for a highly developed system with large storage to recover from a drought. Two or more droughts separated by a few wet years will still appear as critical in this analysis, if the intervening wet years are insufficient for the system to fully recover. As represented here, this is simply a drought identification tool and only very roughly represents what may happen to reservoir storage during a severe sustained drought. In times of severe drought the demand is elastic, and as deficits increase the demand will start to be curtailed as a variety of legal, institutional, social, and economic mechanisms governing water use during drought come into effect. Subsequent papers in this volume consider these issues.

Considering all of this information, the most critical period in the Colorado River basin were the years from 1579-1600, which contained three hydrologic droughts in quick succession (Figure 5b) and represented the most rapid increase in deficit (Figure 5d.). By comparison the largest deficit in Figure 5d accumulates over 150 years, too long a period to consider as a single drought event for this study. However, this does indicate that as the demand approaches

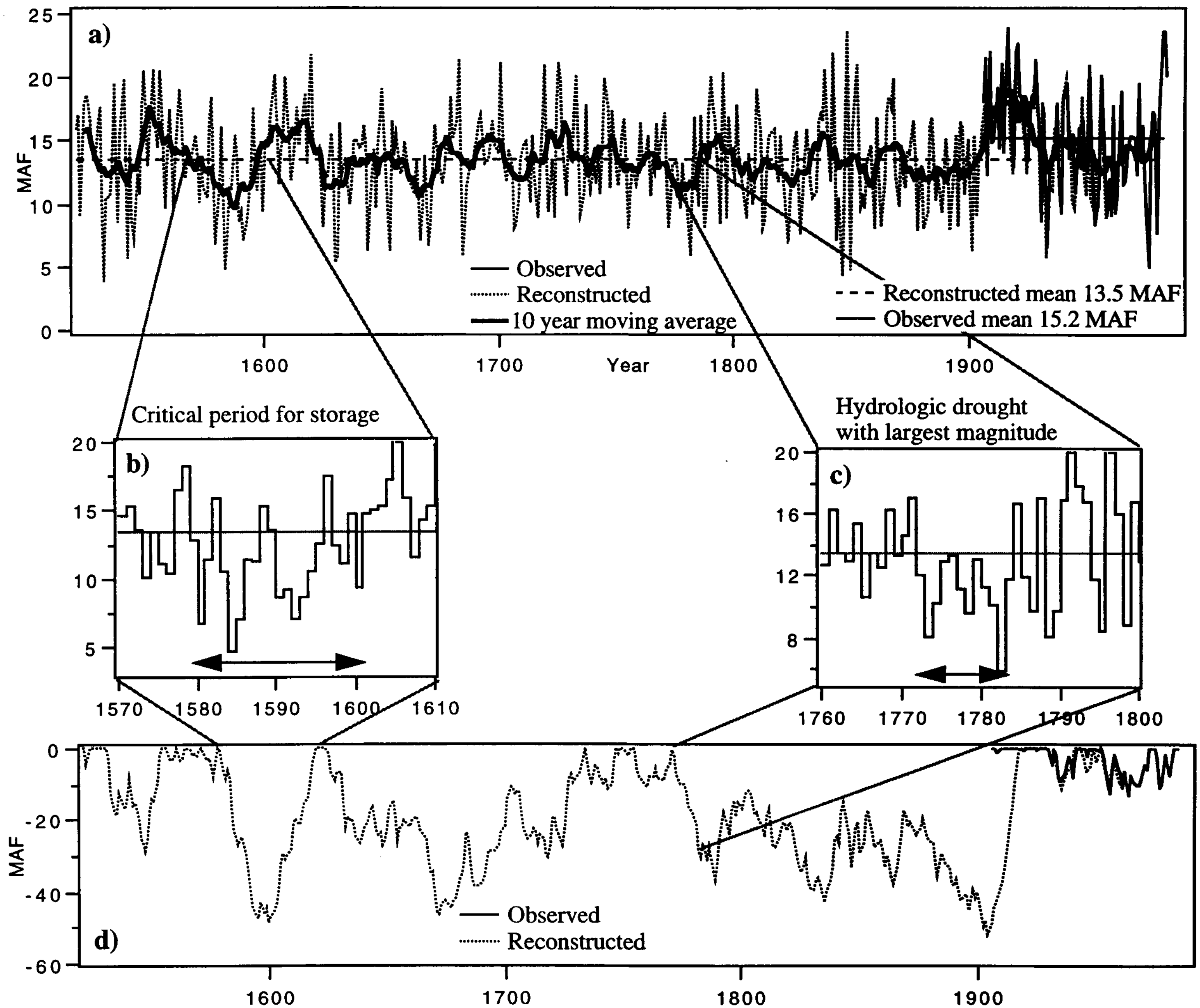

Figure 5. Colorado River at Lees Ferry Drought Identification: a) Streamflow, Annual, and Ten-Year Moving Average; b) Critical Period for Storage; c) Hydrologic Drought With Largest Deficit Magnitude; and d) Storage Deficit With Annual Yield of 13.26 MAF (98 percent of tree-ring reconstruction mean).

the mean flow, very long (150 year) periods with no surplus are possible.

The following drought scenarios were identified and used in this study:

1. **Colorado Drought of Historic Record.** The drought of 1943 to 1964 in the historic unimpaired streamflow record. This is defensible as likely to recur, not withstanding any doubt surrounding the reliability of the tree ring reconstructions.

2. **Colorado Severe Drought.** The Colorado River drought of 1579 to 1600 as reconstructed from tree rings.

3. **Colorado Rearranged Severe Drought.** The Colorado River drought of 1579 to 1600 with annual flows re-arranged to be in descending order in this period. This makes the same amount of water available as in scenario 1, but the extremely low flows are clustered together at the end, when reservoirs are already low or dry. This scenario is somewhat artificial but was included to explore how the system would respond to a truly catastrophic drought. This drought is illustrated in Figure 6. Also shown is the recovery period following the drought, comprising reconstructed streamflow for the years 1601 to 1616. The flows shown here from 1579 to 1616 comprise the 37-year analysis period used by accompanying papers in this volume.

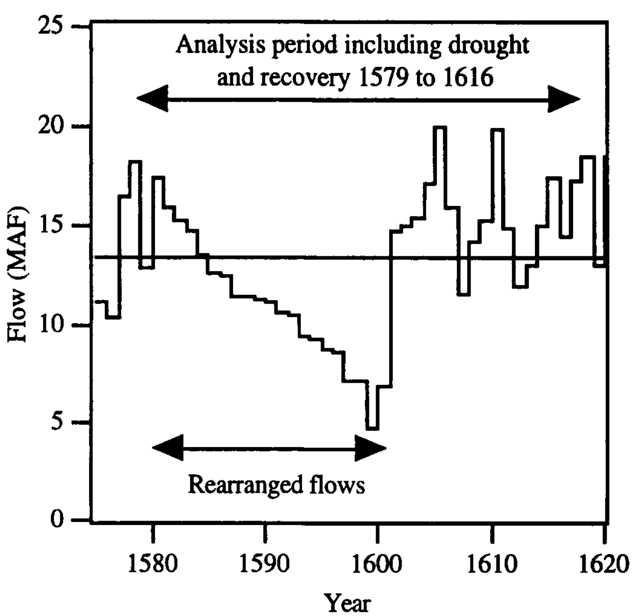

Figure 6. Colorado River Re-arranged Severe Drought and Recovery Period.

One goal of this project was to focus on the geographic impact of drought and the ability of the water management infrastructure and institutions to equitably and efficiently distribute the water that is available. This requires knowledge of the spatial distribution of water for the drought scenarios studied. Models of the water demand and allocation systems, such as the Colorado River Simulation System and California Department of Water Resources model, require monthly inputs at spatially distributed source points. Flows reconstructed from tree rings are aggregate values representing the sum of flows from all sites and seasons. To use these flows for drought planning requires that they be disaggregated into flows at each source site for each season (month). Procedures that are well documented and researched (Bras and Rodriguez-Iturbe, 1985; Grygier and Stedinger, 1988; Loucks *et al.*, 1981; Salas *et al.*, 1980; Stedinger *et al.*, 1985; Stedinger and Vogel, 1984) are available for disaggregation of annual basin aggregate flow into monthly flow at each site.

Here, disaggregation procedures were applied to drought scenarios 2 and 3 developed above. The disaggregation package SPIGOT (Grygier and Stedinger, 1988, 1990a, 1990b) modified to work off tree-ring reconstructed records, rather than annual flows generated from an autoregressive order, one model was used. Details of the implementation and testing of this approach are given in Tarboton (1994). The results provide reasonable estimates of possible spatial configurations of a drought scenario that has been defined by an aggregate Lees Ferry flow, and have been used in the impact analysis described in accompanying papers (Harding *et al.*, 1995; Sangoyomi and Harding, 1995). Drought scenario 1 was in the historic record, and its spatial configuration was already known. Estimated historic unimpaired flows at source locations were used in the study of this scenario.

QUANTIFICATION OF DROUGHT PROBABILITY FOR THE STUDY SCENARIOS

The probability or risk of the drought scenarios developed is required so that planners can be aware of the likelihood of the scenarios studied or similar scenarios actually occurring. Here statistical techniques are used to assess this probability. The evidence from geophysical data is that nature is continually changing with cycles of variability that stretch across years, decades, and even millennia. The assumption that has to be made in quantifying the risk associated with future droughts is that the past is an indicator of the future. One has to assume stationarity and hope that the observed variability of the data about an average is large when compared to the long-term shifts in that average value. This cannot be verified. Models that account for this uncertainty, such as models 3 and 4 below, allow us to hedge our bets. However any planning that makes use of this information needs to recognize the inherent uncertainty in planning for the future.

The basic statistics of the streamflow series studied were given in Table 1. The lag 1 correlation for historic unimpaired flows at Lees Ferry is not significantly different from 0 at the 95 percent confidence level under a statistical hypothesis test based on the variance of the sample correlation (Bras and Rodriguez-Iturbe, 1985, p. 57). This is not a very powerful test due to the shortness of the record, but it could be used to argue against using models with any sort of dependence between annual flows.

The Hurst coefficient has been estimated through rescaled range analysis (Pegram *et al.*, 1980; Bras and Rodriguez-Iturbe, 1985; Feder 1988). Range is defined as the maximum minus minimum cumulative departure from the mean in a sequence of flows n years long. Rescaled range is range divided by standard deviation. The Hurst coefficient is defined as the scaling exponent associated with the increase in rescaled range with sample size. It is recognized that given the length of record this is a highly uncertain statistic.

The likelihood of the drought scenarios developed was evaluated using four models for annual streamflow:

Model 1. Independent annual flows.

Model 2. Autoregressive order one model with fixed parameters.

Model 3. Autoregressive order one model, allowing for parameter uncertainty.

Model 4. Fractional Gaussian noise model using the estimated Hurst coefficient.

These cover the range of models that may be considered reasonable to simulate annual streamflow. The details of these models are given by Tarboton (1994). Model 1 could be justified in terms of the annual lag 1 correlation coefficient (Table 1) not being significantly different from zero. Model 2 (see for example Bras and Rodriguez-Iturbe, 1985) is popular in hydrology. Model 3 accounts for parameter uncertainty by using methods given by Grygier and Stedinger (1990a). Model 4 uses the successive random addition procedure (Voss, 1985; Feder, 1988) to generate Fractional Gaussian noise that approximates long memory and self similarity in the streamflow series.

Drought Scenario Characteristics

The extremely severe drought in the Colorado River from 1579 to 1600 was characterized by a sharp drop in the storage deficits because the 17-year mean streamflow (1579 to 1595) is 10.47 MAF, and the 22-year mean streamflow (1579 to 1600) is 11.05 MAF, both figures being considerably less than the historic mean of 15.2 MAF (1906-1983) and tree-ring reconstruction mean of 13.5 MAF (1520-1961). The Colorado rearranged severe drought (see Figure 6) consists of 16 years with below mean streamflow and is characterized by a 16-year mean of 9.57 MAF.

The basis for assessment of the likelihood of these scenarios was to compute the probability and return period of mean flows below these thresholds for each of the models considered. The approach taken here is different from that of Loaiciga *et al.* (1992, 1993), who used renewal theory to analyze hydrologic drought (sequences of years with streamflow below a threshold). Here droughts are characterized by a mean streamflow below a threshold. This approach is more appropriate where there is large storage, such as in the reservoirs on the Colorado River. A single slightly-above-threshold wet year does not replenish storage and end drought.

Return Periods for Multi-Year Drought Scenarios

Statistically the concept of return period, or recurrence interval, is well understood when talking about instantaneous occurrences. However, care is needed when the occurrences of interest (droughts) are of significant length. In terms of instantaneous occurrences, if the probability of an event in a unit time period is P, the return period is 1/P, measured in unit time periods. Now consider a multiple year event, such as an N year drought. Denote the probability of any N year period being such a drought as P_N. The return period measured in N year intervals is $1/P_N$, or measured in years is $R = N/P_N$. The probability of any one year being in an N year drought is $N/R = P_N$. Note that since P_N is a probability (less than 1) it is impossible to have R less than N, the duration of the drought being considered.

Table 2 summarizes calculations of return period R for each of the drought scenarios developed, using each of the annual streamflow models considered. Table 2 also includes a naive return period estimate, defined as the length of record from which the scenario was taken. Since these scenarios are the most critical in a historic or reconstructed record, this provides a simple estimate of return period. Models 1 and 2 can be solved analytically, so the results given are exact. Models 3 and 4 were solved by Monte Carlo techniques, simulating 10,000 years of streamflow and dividing 10,000 by the number of occurrences of droughts with N year mean less than the N year mean that characterizes the drought under consideration. Details of these calculations are given in Tarboton (1994).

In evaluating the results in Table 2, one needs to bear in mind that the return periods reported are for multiple year events. The probability of any one year selected at random being in that scenario is the scenario duration divided by return period. For example, if the return period of a 20-year duration event is 80 years, the probability of any one year selected at random falling within this drought event is 0.25, rather larger than the commonly perceived risk associated with an 80-year return period event. The scenarios studied, except for the rearranged severe drought, came from either the observed or tree-ring reconstructed historic record.

The historic record drought in the Colorado (1943-1964) is from an 80-year record, and the naive return period estimate of 80 years agrees well with model 3 and model 4 calculations. Models 1 and 2, which either do not reproduce correlation or assume parameters are perfectly estimated, seem to overestimate this return period. This is consistent with the lack of memory in these models. The streamflow mean used to characterize the historic record drought is only just less than the Stockton and Jacoby (1976) reconstruction mean. This explains why return periods only slightly longer than the drought scenario itself are obtained from model estimates based on fits to the tree-ring reconstruction. The severe drought in the Colorado (1579-1600) is from a tree-ring streamflow reconstruction 442 years long. Again the naive return period estimate of 442 years compares well with models 3 and 4, but models 1 and 2 estimate significantly longer return periods.

Overall it can be concluded that models 1 and 2 are biased in their estimate of return period, due to not considering parameter uncertainty and correlation in the case of model 1. Models 3 and 4 give comparable results, bearing out the idea that the Hurst phenomenon which was reproduced by model 4 is equivalent to uncertainty in the underlying process

TABLE 2. Colorado River Drought Return Period Estimates.

	Drought of Historic Record (1943-1964) Scenario 1	Reconstructed Severe Drought (1579-1600) Scenario 2	Re-Arranged Severe Drought of 1579-1600 Scenario 3
Characterizing Flow Mean (MAF*)	13.43	10.47 or** 11.05	9.57
Duration (years)	22	17 or** 22	16
	Return Period (years)	**Return Period (years)**	**Return Period (years)**
Naive	80	442	
Models Fitted to Unimpaired Historic Flows			
Model 1	970	9.9×10^6	3.6×10^8
Model 2	422	2.2×10^5	3.4×10^6
Model 3	107	5,000	> 10,000
Model 4	83	645	2000
Models fitted to Stockton and Jacoby (1976) Tree-Ring Reconstruction of Streamflow			
Model 1	49	38,000	3.3×10^6
Model 2	47	2,500	29,000
Model 3	32	555	4,000
Model 4	32	526	2857

*MAF (million acre-feet) = acre feet x 10^6 = 1.23×10^9 m^3.
**The reconstructed severe drought can be characterized by either a 17-year mean of 10.47 MAF or a 22-year mean of 11.05 MAF. The smaller return period (and corresponding higher probability) associated with these is reported here, because flow below either of these constitutes the drought scenario.

Note: Model 1. Independent Annual Flow; Model 2. Autoregressive Order 1 With Fixed Parameters; Model 3. Autoregressive Order 1 With Uncertain Parameters; and Model 4. Fractional Gaussian Noise. Once model parameters are estimated using either the historic unimpaired or tree-ring reconstructed streamflow, they are used to estimate return period for drought scenarios derived from both historic unimpaired and tree-ring constructed streamflow.

parameters and possible nonstationarity of these parameters that cannot be resolved given the amount of data available. Risk assessment is based primarily on models 3 and 4. The following are proposed as reasonable estimates of the range of uncertainty associated with the return period of each scenario:

1. Colorado Drought in Historic Record (1943-1964): 50 to 100 years.
2. Colorado Severe Drought (1579-1600): 400 to 700 years.
3. Colorado Rearranged Severe Drought: 2000 to 10,000 years or more.

The ranges reflect uncertainty in these estimates. We believe that given the information at hand, it is not possible to meaningfully reduce these ranges. Scenario 1 is therefore a once-in-a-lifetime type of occurrence, scenario 2 occurs less frequently, and scenario 3 is extremely rare or even unrealistic. Nevertheless, scenario 3 was the most interesting to analyze in the context of water shortages since it resulted in Lake Powell being drawn down to dead level. The subsequent papers focus most of their analysis on this scenario. This has been the basis for some criticism of the overall approach. However, this scenario could be viewed as a "probable extreme drought," and its analysis is still useful in focusing on the consequences of severe sustained drought. It is a testament to the reliability of water resources systems in the Colorado River basin that it takes a drought such as scenario 3 before any really extreme consequences are felt.

CONCLUSIONS

Drought scenarios have been developed for the study of severe sustained drought in the Colorado River basin. These scenarios were based on estimated unimpaired and tree-ring reconstructed streamflow. Some discrepancies between different streamflow reconstructions were noted. A variety of stochastic models including independent, autoregressive order one, and fractional Gaussian noise were used to estimate the return period and risk associated with the drought scenarios developed. These occurrence risks should be borne in mind when evaluating and developing planning strategies based on these scenarios.

ACKNOWLEDGEMENTS

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