LONG-TERM SURFACE-WATER SUPPLY AND STREAMFLOW TRENDS IN THE UPPER COLORADO RIVER BASIN BASED ON TREE-RING ANALYSES

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March 1976

LAKE POWELL RESEARCH PROJECT

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Advanced Environmental Research and Technology in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: (1) level and distribution of income and wealth generated by resources development; (2) institutional framework for environmental assessment and planning; (3) institutional decision-making and resource allocation; (4) implications for federal Indian policies of accelerated economic development of the Navajo Indian Reservation; (5) impact of development on demographic structure; (6) consumptive water use in the Upper Colorado River Basin; (7) prediction of future significant changes in the Lake Powell ecosystem; (8) recreational carrying capacity and utilization of the Glen Canyon National Recreational Area; (9) impact of energy development around Lake Powell; and (10) consequences of variability in the lake level of Lake Powell.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make timely research results readily accessible to user groups. The Bulletins supplement technical articles published by Project members in scholarly journals.

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ABSTRACT

The long-term annual runoff has been reconstructed for 12 selected streamgage stations within the Upper Colorado River Basin. The particular stations studied were chosen because of (1) their comparatively long and relatively unmodified flow records which were available for use in calibration processes, (2) their proximity to major runoff-producing areas, and (3) their location relative to existing dendrochronologic (tree-ring) sites. These gaged records were analyzed to determine homogeneity, streamflow trends, and periodicities, and were compared to other records within the Basin. The records revealed several similarities and dissimilarities in trends and periodicities, and were in turn compared to tree-ring data for synchronous time periods and coherency.

Three long-term (from 1512 through 1961) reconstructed hydrographs for the total annual flow at the Colorado River Compact Point (Lee Ferry, which is on the Colorado River at the boundary between the Upper and Lower Basins) were calculated and compared. Based upon these hydrographs, the mean annual virgin flow from the Upper Basin is estimated to be 13.5 million acre-feet. These records also show that the early part of the twentieth century (1906 through 1930) was one of anomalously persistent high runoff from the Colorado River Basin, and that it apparently was the greatest and longest high-flow period within the last 450 years. This wet period was preceded by a long, persistent, low-flow period (1870 through 1894). Only one other low-flow period of comparable length and duration occurred (1566 through 1595). There have been no analogous low-flow periods since gaging was initiated on the Colorado River.

Comparison of long-term reconstructed hydrographs for the Green River above Green River, Utah, the Colorado River above Cisco, Utah, and the San Juan River above Bluff, Utah, shows that the past flow regimes of these rivers possess similarities and dissimilarities.

When the results of our analysis are viewed in the context of future demand for water usage in the Upper Colorado River Basin, it is apparent that projected demand could soon outstrip the natural annual supply of surface water. This situation probably would necessitate shifts in water-use priorities, with current agricultural and recreational allotments being diverted to those needed to meet energy, municipal, and industrial demands.

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INTRODUCTION

Statement of the Problem

There are two main reasons why determining the long-term streamflow trends in the Upper Colorado River Basin (UCRB) is important. The first reason is that the trends in streamflow or surface-water runoff will influence (a) the amount of storage in Lake Powell, (b) the amount of power that can be generated, and (c) the recreational use of the lake. The second and more important reason is that streamflow trends relate to the total surface-water supply in the UCRB. As the major source area for the entire Colorado River Basin water supply, these Upper Basin trends also influence the surface-water supply for the entire Colorado River Basin and its service area (Figure 1). (The service area is defined as those regions external to the UCRB which depend upon Colorado River water for a significant portion of their water supply; examples include the Salt Lake City, Denver, and Southern California metropolitan regions and the Imperial Valley irrigated agricultural region.)

It should be noted here that there is an integrated surface- and ground-water supply for the Colorado River Basin. However, at the present time the Lower Colorado River Basin (LCRB) is using ground water faster than it is being naturally replenished (Arizona Water Commission, 1975; U.S. Department of the Interior, 1974). Therefore, the LCRB should not rely heavily upon accelerated or increased development of ground-water resources in order to compensate for water shortages in the future. With regard to the UCRB, many of the ground-water resources are directly related to streamflow and they cannot be developed without some disturbance of the surface-water flow. In other areas the ground-water resources are more separated from streamflow.

There also are serious water-quality problems in some of the ground-water regions of the Upper Basin. The region is generally classified as arid to semi-arid, and the ground-water replenishment rate is comparatively low. Therefore, unless careful, judicious development of ground-water resources is applied, the Upper Basin could find itself mining ground-water, a situation similar to that in the Lower Basin, and thereby only postponing a water crisis in the Upper Basin.

With careful development of the renewable ground-water resources of the Upper Basin, there may be a significant addition to the overall water supply in the Upper Basin for an indefinite period of time. The major problem relating to Lake Powell and the surface-water supply of the Upper Basin is to determine what the streamflow trends are and what the long-term average flow has been and is likely to be in the future.

A recent study by the U.S. Department of the Interior (1974) suggested that there may not be enough water to meet projected needs in the UCRB, especially considering the projected increased quantities needed for energy, export purposes, and food and fiber production. The report indicates that Wyoming is the only UCRB state that has enough water to meet the needs of all

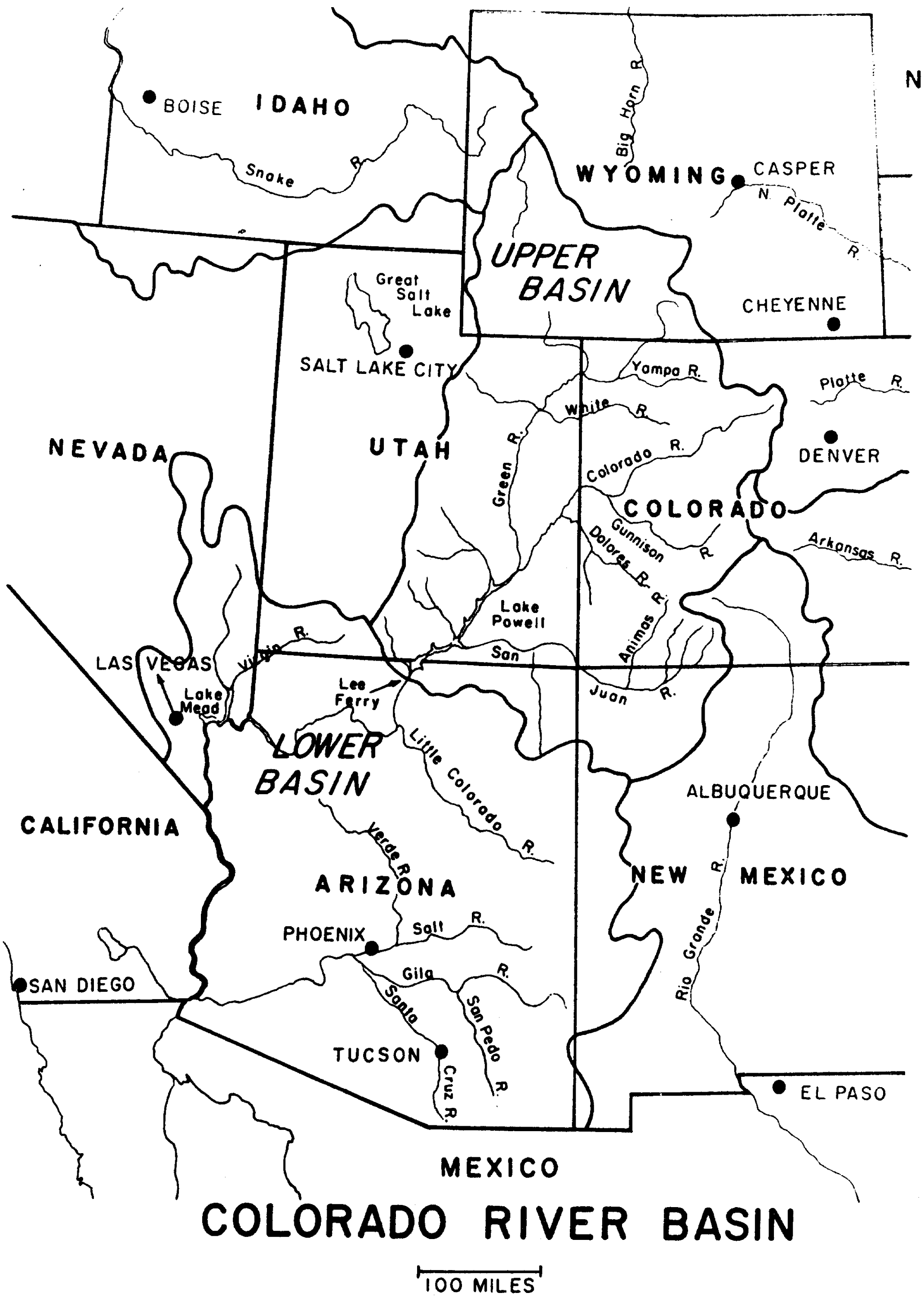

Figure 1: Map of the Colorado River Basin Showing Major Cities in and near the Basin and Lee Ferry, the Division Between the Upper and Lower Basins and the Colorado River Compact Accounting Point.

these anticipated developments. The Upper Basin states originally were apportioned the annual consumptive use of 7.5 million acre-feet (maf) of water by the 1922 Colorado River Compact, Article III (a). Historically, the Upper Basin has not utilized its entire apportionment and much of its allowable depletion has passed to the Lower Basin. This has created an inaccurate sense of surplus in some minds, but closer examination (described in this Bulletin) based upon tree-ring analyses shows that the UCRB is in fact headed for a water shortage. Based upon preliminary results, it is estimated that the long-term mean annual virgin runoff at Lee Ferry, Arizona, is 13.5 maf and not the approximately 16.2 maf anticipated when the water rights were divided according to the 1922 Colorado River Compact (U.S. Department of the Interior, Bureau of Reclamation, 1928, cited in House Doc. 446, 1928, p. 9). Furthermore, it is apparent from our work that the period from 1906 through 1930 was the greatest extended period of high surface runoff from the UCRB within the last 450 years. Consequently, any estimates of future flow that are based on periods of record which include this wet interval tend to be inflated. On the other hand, throughout the recorded streamflow records from 1896 through 1971 there have been no extended periods of drought comparable to those of the late 1500s or late 1800s. The possible occurrence of such extended periods of low flow also should be taken into account in decisions concerning water resources. The tendencies for extreme (either wet or dry) years to occur in clusters and for the periods to be especially extreme have been described by Mandelbrot and Wallis (1968), who named this phenomenon the "Noah and Joseph effect" after the well-known Biblical personalities.

We feel that these "effects" are a critical part of the temporal runoff regime and must be considered in decision-making processes regarding water resource development and allocation in the UCRB. Therefore it is important to know the estimated duration, frequency, and amplitude of extreme events as well as the long-term mean figures. This Bulletin will consider mainly the long-term mean values. Further dendrohydrologic analyses will emphasize the other aspects of flow reconstruction.

Objective of the Study

This investigation has used hydrologic information inherent in long-duration tree-ring series to reconstruct past records of runoff from major runoff-producing areas within the UCRB. It has been shown that dendrochronology can be used to determine climatic variation and streamflow trends in various areas of the Southwest (Stockton, 1975). The present study has generated new data from tree-ring sites in the UCRB and has assembled current and more accurate estimates of virgin runoff for the Upper Basin. Dendrochronologic techniques used to estimate streamflow have been applied to this new block of data in order to determine streamflow trends and parameters in the UCRB. This general approach is not new and in fact was applied previously to the UCRB by Schulman (1945), who utilized tree-ring data from the Upper Basin to study past drought conditions within the area. His study was designed to assist in wartime decisions concerning dependability of power generation at Hoover Dam. Schulman's technique was to sample a single core from a single tree and to consider the ring-width measurements from that core as the best estimate of the climatic chronology from the site.

The science of dendrohydrology has progressed substantially since Schulman's work in the late 1930s and early 1940s. Due primarily to the work of H. C. Fritts of the Laboratory of Tree-Ring Research at the University of Arizona in Tucson, a reliable standard procedure has been developed. Fritts' procedure is to sample at least ten trees on a given site and to average the chronologies from at least two cores per tree into a mean-value function that represents the best estimate of long-term climatic conditions at that site. Recently, Fritts (1976) also designed multivariate statistical techniques that allow calculation of climatic-response functions on a month-by-month basis for any given site of trees. Both the total monthly precipitation in an area and the average monthly temperature effects on tree growth can be deciphered from the tree-ring record, and the result can then be used to reconstruct past climatic and hydrologic conditions. These techniques have been of tremendous value in showing that the climatic signal in the tree-ring series corresponds to that within a synchronous runoff series (Stockton, 1975). Thus, the objectives for our study have been to generate new data for the Upper Basin and, through the application of modern dendrohydrologic techniques, to determine more accurately the long-term streamflow trends and parameters in the UCRB.

Previous Studies

Many other attempts have been made in the past to evaluate both the spatial and temporal variabilities in surface runoff from and within the UCRB. Perhaps the earliest is that by LaRue (1925). The most recent, and perhaps most complete, is that by Iorns et al. (1965). The data in Iorns et al. are based on U.S. Geological Survey (USGS) streamflow measurements and represent the flow information based on measured data up until the year 1957. Thus, there is available since 1957 almost two decades of new streamflow information. Others have looked at particular aspects of the flow variability: Leopold (1959) applied probability analysis to the flow record at Lees Ferry, and Julian (1961) utilized spectral analysis to analyze the record for periodicities and persistence.

As part of its basic data collection program, in 1922 and 1923 the USGS established gages in the UCRB to measure the major tributaries in the Upper Basin and also the streamflow at Lees Ferry and the Paria River just above the Colorado River Compact Point (Lee Ferry). With each succeeding year of measurement since then, these data are averaged with those from earlier years to produce an overall annual average; this is a continually changing average, since each new year is either above or below the mean and moves the average in that respective direction. Each year's measurement is another sample of the annual flow population; the more samples available, the greater the likelihood that the sample mean is close to the real population mean. The USGS, however, only records information on measured flow. Consumptive use in the Upper Basin must be estimated and added back to this gaged flow to develop a figure which is an estimate of the undisturbed or virgin runoff from the Upper Basin.

In order to evaluate the potential for and effects of various hydroelectric projects and water-storage projects in the Upper Basin, the Bureau of Reclamation has estimated the streamflow at various ungaged locations in the Upper Basin. These estimated records are based on measured records at other stations. Correlation analysis or averaging was used to prorate information from appropriately chosen stations, and estimates were made for streamflow at particular points of interest to the Bureau for their various projects.

The early efforts of the Lake Powell Research Project (LPRP) in studying streamflow trends also consisted of analyses of USGS streamflow data. The results of these analyses are summarized in the following section of this Bulletin and are more fully described in the 1972 LPRP Progress Report to the National Science Foundation (Jacoby and Anderson, 1972). There is also a detailed analysis of the Whiterocks River in the Uinta Mountains that is based on tree-ring data. This study is in the 1973 LPRP Progress Report to the National Science Foundation (Jacoby and Stockton, 1973).

SURFACE-WATER HYDROLOGY

Major Runoff-Producing Areas

The UCRB comprises approximately 109,300 square miles and has a great range of physical characteristics. Much of the region can be termed arid to semi-arid, with typical dry-area vegetation and low precipitation. Other mountainous areas of this region are forested and have much greater precipitation.

Analysis of streamflow measurements from the USGS indicates that almost 85 percent of the runoff from the entire UCRB originates in only 15 percent of the area. This 15 percent includes all of the high mountainous areas in the Upper Basin where, due to orographic precipitation, the streamflow per unit area is much greater than it is in the lower, dryer portions of the Basin. These major runoff-producing areas (shown in Figure 2) coincide with the Wind River Mountains in Wyoming, the Uinta Mountains along the Wyoming-Utah border, the central Rocky Mountains extending from southern Wyoming down through Colorado, and a portion of the southern Rockies in southwestern Colorado. The major portion of the precipitation occurs in these mountainous areas during the winter, when it builds up as a heavy snowpack. Upon the approach of warmer weather, this snow melts and produces the spring runoff which is the major contributor to surface-water flow in the Upper Basin. As the seasonal change moves from the winter towards the warmer summer months, the southernmost mountains which feed the San Juan River experience a spring-runoff condition, and the San Juan River reaches its maximum annual flood stage in about April. As the warmer weather progresses toward the north, the central Rockies, Uintas, and the Wind River Mountains also produce a spring runoff which occurs in May or June, 4 to 6 weeks later than the major flow of the San Juan River. This later spring runoff contributes the major flow to both the Colorado River Main Stem and the Green River. During the summer months there is also a monsoon effect in the UCRB, and there are more localized summer storms that produce significant amounts of runoff in the Upper Basin. On occasion there are large-scale storms during this period that produce great quantities of runoff, such as occurred on the San Juan River in the late summer of 1972; but generally the major contribution to streamflow comes from the winter snowpack in the UCRB.

A more detailed breakdown of UCRB runoff with respect to subbasins is shown in Table 1, where the percent contribution to the annual runoff from the UCRB is also shown. As can be seen, these seven subareas contribute an estimated 85 percent

Table 1: Seven Subareas within the Upper Colorado River Basin Which Contribute the Majority of the Mean Annual Runoff[a]

Number	Subarea	Percent Contribution
1	Wind River Mountains, Northwestern Wyoming	9
2	Uinta Mountains, Northeastern Utah	9
3	Yampa and White Rivers Headwaters, Northwestern Colorado	14
4	Mainstream Colorado River Headwaters, West-Central Colorado	18
5	Gunnison River, West-Central Colorado	16
6	Dolores River, Southwestern Colorado	5
7	San Juan River Headwaters, Southwestern Colorado	14
	Total	85

[a]Based on data from USGS Water Supply Papers, Nos. 1313, 1733, 1924, and 1925.

of the mean annual runoff from the UCRB. For this reason, we have concentrated our research on tree-ring sites in these areas.

Subareas 1, 2, and 3 (Table 1) are within and tributary to the Green River Basin, and they contribute an estimated 32 percent of the mean flow of the Upper Basin. The Green River as gaged at Green River, Utah, contributes 35 percent of the gaged streamflow at Lees Ferry. This increase is due to contributions from lower tributaries. (These figures and those which follow are based on data for the years 1914 through 1965 that were obtained from USGS Water Supply Papers 1313, 1733, 1924, and 1925.) Subareas 4, 5, and 6 are within the drainage area of the Colorado River above Cisco, Utah, and they contribute 39 percent of the mean annual outflow from the Upper Basin. The runoff recorded near Cisco contributes 44.8 percent of the total runoff at Lees Ferry. The headwaters of the San Juan River, subarea 7, contribute 14 percent of the total runoff, whereas the runoff near Bluff, Utah, represents 15.6 percent of the total flow at Lees Ferry, Arizona. These figures are summarized in Table 2. There is additional tributary flow into the rivers from areas outside the numbered subareas. Therefore the percentages for the three main gaging sites are higher than the sum of the subareas.

From the data in Table 2, we assume the period of record we have used to be representative of proportional flow, and therefore that the runoff from the Upper Basin as gaged at Green River, Cisco, and Bluff, Utah, accounts for approximately 95.5 percent of the gaged record at Lees Ferry, Arizona.

Table 2: Breakdown of Contributions of Major Tributaries to Total Outflow from the Upper Colorado River Basin, and Percentage Contribution of Selected Subareas Within Each of the Tributary Basins (All Values Based on Water-Years from 1914 through 1965)

Tributary	Mean Annual Flow (acre-feet)	Contribution to Gaged Outflow at Lees Ferry, Arizona (percent)	Pertinent Subareas (from Table 1)	Subarea Contribution to Gaged Outflow (percent)
Green River above Green River, Utah	4,502,860	35.1	1,2,3	32.0
Colorado River above Cisco, Utah	5,751,920	44.8	4,5,6	39.0
San Juan River above Bluff, Utah	2,004,370	15.6	7	14.0
Total	12,259,150	95.5		85.0
Total Gaged Outflow at Lees Ferry	12,842,000	100.0		

Differences in Runoff Trends (Based on USGS Measured Data)

Background

The streamflow records used in this study were chosen on the bases of length, accuracy, and continuity. The basins and gaging stations were examined in the field in 1971 on a reconnaissance basis in order to determine modifications by man or nature that would distort the records. Documentation of diversions for irrigation and other purposes was reviewed, and individual records were selected for those areas in which there was the least interference with natural flow. In a few cases, diversion records were added to measured flow to recreate the unmodified flow record. All runoff figures or discharges used were expressed in terms of the number of acre-feet per water-year.

For discussion purposes, a distinction must be made between measured streamflow and estimated or reconstructed virgin flow. Measured streamflow, also termed historical flow, is determined by USGS gaging stations. Since there are numerous sources of error in streamflow measurements, for analytical purposes the quality of the data must be considered. In this study, only those stations receiving a rating of "Good" or better for most of the record were used. "Good" means that for at least 85 percent of the time the measurement is believed to be within ± 5 percent of the actual flow. Virgin flow represents what the streamflow would be if there were no diversions or consumptive use above the gaging point. Virgin flow can be estimated by adding values for diversions and consumptive use to the measured flow. The following discussion is based on measured streamflow values, although in a few cases quantified diversions and reservoir storage changes have been added to measured flow in order to approximate natural flow.

Green River Subdivision

The Green River subdivision of the UCRB contributes about 35 percent of the gaged flow at Lees Ferry and can be divided as follows:

Wind River Region (Estimated Contribution of 9 Percent)

The longest usable recorded streamflow record in the Wind River region was taken on the New Fork River near Boulder, Wyoming, which comprises a drainage area of 552 square miles. This record does not show a well-defined, long-term trend. However, the low flows shown in records from about 1961 are not as low as were those for the previous dry period, which centered around 1935. There also appears to be a periodicity of about 25 years' duration between both the high and low extremes.

Data from the Green River area at Warren Bridge, Wyoming, do not extend back to the high flows of the early 1920s; however they do duplicate both the low flow of the mid-1930s and the second (less severe) low centered around 1961. A period of high flow was recorded in the early 1950s, and the record suggests the approach of another high-flow period in the near future.

Another important record in the Wind River region comes from North Piney Creek, near Mason, Wyoming. This record is similar to that of the Green River station at Warren Bridge.

Considering these three records (New Fork River, Green River, and North Piney Creek) as a composite, the following picture can be drawn: (a) there was a wetter period in the early 1920s which declined to a severe dry period in the mid-1930s; (b) this was followed by an increase to a wet period in the early 1950s equal to that of the 1920s; (c) then came a less severe low in the late 1950s; and (d) based primarily on records from the Green River station, a new wet period began during 1962-1963. Thus it can be seen that the Wind River region has an apparent 25-year periodicity superposed on an overall slightly upward trend for the period of recorded data.

Uinta Mountains Region (Estimated Contribution of 9 Percent)

The longest usable recorded streamflow record in the Uinta region was taken on the Whiterocks River near Whiterocks, Utah, on the south side of the Uinta Mountains. The basin above this gage comprises an area of 115 square miles. This record shows an extremely wet period extending from near the turn of the century through the mid-1920s; a dry period in the mid-1930s; a wet period in the early 1940s; a dry mid-1950 period; and a trend toward a wetter period from then on. This record is one of the best from the entire UCRB region, as there are almost no modifications of natural flow and it is a long, good-quality record. The record displays a long-term downward trend superposed on approximate 24-year periodicities; however, presently the trend is upward.

The best streamflow record from the north side of the Uinta Mountains is that taken from Henrys Fork at Linwood, Utah, with a drainage area of 520 square miles.

However, it is not as long as that taken from the Whiterocks River. The record shows an apparent strong wet trend at the time of this writing. This trend is also shown by the record from East Fork of Smith Fork near Robertson, Wyoming. (Henry's Fork and East Fork of Smith Fork are tributaries to the Green River.) However, there is no streamflow record on the north flank of the Uinta Mountains that extends back over the wet period of the beginning of this century. Therefore, one can say only that there is an apparent wetter trend since 1930 and, as in the Wind River region, a periodicity of approximately 24 years.

Yampa and White River Region (Estimated Contribution of 14 Percent)

The best recorded streamflow record in the Yampa-White River region was taken on the Elk River at Clark, Colorado. The basin above this gage comprises an area of 206 square miles. The record shows the wet period of the early 1900s and a long dry period around 1940. It also shows a small increase in flow in the late 1940s, and then a gradual decline to the present time.

Records from the Little Snake River near Lily, Colorado, parallel the same trends. At this particular location, the Little Snake drains an area of 3,730 square miles.

The 1930s dry period was found to occur later in the Yampa-White River area than in the Uinta and Wind River areas. There appears to be an approximate 20-year periodicity. The strong upturn to a wetter period in the late 1960s that has been reported previously is absent in this record. Thus, even when the earliest wet period is excluded from consideration, there is indication of a gradual drier trend occurring over the periods of record for this area.

Summary of Green River Subdivision

The Green River subdivision is complex and differs from the two subdivisions (the Colorado and San Juan) to the south. The Uinta and the Wind River Mountains regions appear to be moving into a wetter phase. The Yampa-White River region is paralleling the trends of the two southern regions (which are discussed later) and is following a drier trend. The barrier of the Uinta Mountains and different prevailing air mass movements separate the northern extension of the UCRB from the larger southern section. The line of separation runs roughly east to west and just south of the Uinta Mountain Divide (Fritts and Cathey, 1971).

Colorado River Subdivision

The Colorado River subdivision of the UCRB contributes about 45 percent of the gaged flow at Lees Ferry and can be divided as follows:

Main Stem Colorado Headwater Region (Estimated Contribution of 18 Percent)

Almost every significant stream in the Main Stem Colorado headwater region has substantial diversions, many of which are transmountain diversions that go to the east side of the Continental Divide. Almost all of the streamflow records from this region have to have their diversion figures restored to give a realistic picture of the natural flow.

The Fraser River near Winter Park, Colorado, drains an area of 27.6 square miles. Even from this small basin there are two significant diversions: one is to the Berthoud Pass ditch and has been in existence since 1910; the other is the Moffat water tunnel and has been in existence since 1936. The diversion values from these two have been measured, and therefore the restored figures should be accurate. The early wetter period is evident from the data in the streamflow record. There appears to be a 10- to 11-year periodicity imposed on a steadily declining flow. The decline is apparent even if the unusually wet period of the early 1900s is excluded from consideration.

Gunnison River Region (Estimated Contribution of 16 Percent)

The Taylor River at Almont, Colorado, is the most useful streamflow record in the Gunnison River region. It comprises a drainage area of 477 square miles. The flow has been regulated since 1937 by the Taylor Park Reservoir, whose capacity is 106,200 acre-feet. The reservoir is situated at over 9,000 feet above sea level in a cool mountain environment. The 55-year mean flow at the river gage is 246,100 acre-feet per water-year. The reservoir acts as a flow attenuator, but there is no diversion out of the Gunnison River Basin above this point. The net change in reservoir contents for the entire year can be added back to the measured flow to restore the flow data to undisturbed values.

The apparent trend in the Gunnison River area is a descent from the early wet period to a low centered around 1940. This decline is followed by a small increase, which in turn is followed by another decline which does not reach the previous low of about 1940.

Kannah Creek near Whitewater, Colorado, is also in the Gunnison River area, and its drainage area comprises 61.9 square miles. There is a diversion for municipal water supply, but figures adjusted for this diversion are available and were used for the analysis. The Kannah Creek data show an approximate 16-year periodicity superposed on a definite declining trend. The late decline of the 1960s is probably representative of the entire Gunnison Basin area.

Dolores River Region (Estimated Contribution of 5 Percent)

The best recorded streamflow in this area is from the Dolores River at Dolores, Colorado. The Dolores River drainage area comprises 556 square miles. There is a small reservoir above the gage, but its total capacity is less than 7 percent of the mean annual flow, so any changes in storage should have only a small effect on the data. There are two gaps in the early portion of the record. They occur during the rise into the wet period in the early part of this century, but the data for much of this wet period are recorded at this station.

There is an approximate 19- to 20-year periodicity superposed on a declining trend. This declining trend is apparent, as in the Main Stem Colorado and Gunnison regions, even if the earliest wet period is disregarded.

Summary of Colorado River Subdivision

In the Colorado River subdivision as a whole, the recorded streamflow trend has declined from a very wet period centered around 1918 to the present drier period. Individual records show cyclical natures, but the lengths of the short-term periodicities are not consistent throughout the subdivision.

San Juan River Subdivision

The San Juan River subdivision of the UCRB contributes 16 percent of the gaged flow at Lees Ferry. Only one subbasin was studied.

San Juan Region (Estimated Contribution of 14 Percent)

The Navajo River at Edith, Colorado, comprises an area of 172 square miles. There is a diversion above the station, and the water is used to irrigate approximately 1.5 percent of the San Juan River Basin area. There appears to be an approximate 20- to 22-year periodicity superposed on a declining trend.

Two other shorter streamflow records (one from the Florida River near Durango, Colorado, and the other from the Animas River at Howardsville, Colorado) show that the declining trend of the last several decades persists throughout the entire San Juan River Basin area.

Thus the trend since 1913 for the San Juan River subdivision is distinctly downward, based on the Navajo River station records. The drought which affected much of the western part of the nation during the 1930s appears to have been a lesser event in this subdivision than was the dry period of the last few decades. The individual year of 1951 is the driest on this record. During 1951, the San Juan River subdivision contributed less than 10 percent of the gaged flow at Lees Ferry.

Summary

The foregoing analyses of measured streamflow-trend data indicate that the UCRB is not climatically homogeneous. The northern region (including the Green River subdivision) appears to be trending toward a wetter period, and, below the Uinta Mountains climatic divide, the southern regions (including the Colorado River and San Juan River subdivisions) appear to be trending towards a drier period.

There are seemingly periodic variations, but in many cases the lengths of the available records are barely long enough to show much more than one complete cycle. Also, the apparent periodicities are not consistent throughout the UCRB. It was because so many uncertainties resulted from the analyses of measured data that our present dendrohydrologic analyses were undertaken. These analyses are described in the following section.

DENDROCHRONOLOGY

The primary objective of our study was to reconstruct long-term runoff records for major runoff-producing areas within the UCRB for the three main rivers (the Green, Colorado, and San Juan) and for the Upper Basin as a whole. Therefore, we utilized tree-ring series data from as many of the major runoff-producing areas as was possible. For many of these areas, we were fortunate that long, climatically sensitive, tree-ring series had been collected for other projects. For other areas, it was necessary to obtain tree-ring samples specifically for the LPRP. All the samples were collected using a small-diameter

Swedish increment borer so that the trees would sustain no permanent injury.

In referring to Figure 2, the reader will see the spatial distribution and the relationships to major runoff-producing areas of the 30 different tree-ring sites used in this study (11 of which were developed specifically for this study). Table 3 is a list of the individual sites, and it shows some of the important statistical details of the individual series. In addition to the period of record for each of the series, the first-order autocorrelation coefficient (R_1), the coefficient of mean sensitivity (MS), and the standard deviation (SD) are also shown. These three statistics respectively provide measures of persistence, high-frequency variation, and total variation in the tree-ring data series. The statistics are described in more detail in Stockton (1975). In general, the more climatically sensitive series have the following approximate values: R_1 = 0.20 to 0.30; MS = 0.35 to 0.45; and SD = 0.35 to 0.45 (Stockton, 1973). As can be seen from scanning the statistics of the 30 data series listed in Table 3, some of the series do not possess statistics equal to those of the more climatically sensitive series. However, it is our belief that in certain cases the positions of the sites within the UCRB relative to major runoff-producing zones were more important for utilizing some of the data series in runoff reconstruction than was maximizing the climatic sensitivity.

All of the tree-ring series used in Table 3 are mean-value functions; that is, at least two series from each tree were averaged in order to provide the best estimate of the series from that tree. A multitude of tree series comprises a site series. Normally, at least ten trees were sampled at each site. At the Uinta D site (Number 9 in Table 3 and Figure 2), however, only four trees (eight core series) were sampled because of the small number of trees suitable for sampling.

The objective of having a ten-tree minimum at each site (two radii sampled from each tree) was based on prior experience of the staff at the Laboratory of Tree-Ring Research. In western North America we have found that sampling a "climatically homogeneous" site in this manner gives a mean-value function which maximizes the climatic signal representative of that site and which minimizes the noise signal that comes from the idiosyncrasies of individual trees. Because our ultimate objective required the use of the climatic signal inherent in the tree-ring data, we were particularly anxious to utilize techniques that would maximize that signal.

The climatic sensitivity of a particular tree-ring series is controlled by the conditions of the site upon which the sampled trees are growing. Ideally, the site selected is one which is at or near the limit of the natural distribution of the species and is located on a sloping surface where soil development is negligible. However, in many instances, the overriding factor is a location relative to a watershed boundary or to a certain climatic station that is to be used for calibration. In the present study, we had one additional factor to consider, and that was whether we had access to a previously collected site series in the vicinity of the needed location. With limited funding, only the most crucial areas could be justified economically for new site collections. Each new site collection involves a rather large investment which includes not only the collecting but

Table 3: Tree-Ring Data Sites

Number on Figure 2	Station Name	Identification Number[d]	Period of Record[e]	R_1 [f]	MS [g]	SD [h]
1	Wind River Mountains, C, Wyoming[a]	282540	1504-1971	0.54	0.20	0.25
2	Wind River Mountains, D, Wyoming[a]	283590	1492-1971	0.51	0.20	0.27
3	Wind River Mountains, B, Wyoming[a]	101540	1568-1971	0.55	0.26	0.33
4	Wind River Mountains, A, Wyoming[a]	102590	1678-1971	0.52	0.44	0.50
5	Uinta Mountains, North, Utah[a]	281550	1605-1971	0.43	0.17	0.19
6	Uinta Mountains, A, Utah[a]	277550	1433-1971	0.71	0.11	0.18
7	Uinta Mountains, B, Utah[a]	278540	1730-1971	0.47	0.30	0.36
8	Uinta Mountains, C, Utah[a]	279540	1635-1971	0.55	0.33	0.40
9	Uinta Mountains, D, Utah[a]	280620	1423-1971	0.46	0.31	0.33
10	New North Park, Colorado[b]	110549	1354-1964	0.51	0.33	0.39
11	Chicago Creek, Colorado[b]	115549	1441-1964	0.25	0.40	0.38
12	Idaho Springs East, Colorado[b]	114540	1710-1964	0.40	0.36	0.40
13	Eagle, Colorado[b]	112549	1107-1964	0.60	0.30	0.41
14	Eagle East, Colorado[b]	113629	1314-1964	0.39	0.29	0.30
15	Nine Mile Canyon, Utah[b]	123549	1194-1964	0.44	0.42	0.45
16	Escalante Forks, Colorado[b]	119620	1640-1964	0.22	0.38	0.34
17	Black Canyon, A, Colorado[b]	118629	1457-1964	0.36	0.22	0.23
18	Black Canyon, Colorado[b]	117549	1478-1964	0.52	0.30	0.37
19	Upper Gunnison, Colorado[b]	116549	1322-1964	0.37	0.37	0.40
20	La Sal Mountains, A, Utah[a]	285620	1489-1972	0.41	0.34	0.35
21	Bryce Canyon, Utah[b]	131549	1270-1964	0.53	0.26	0.31
22	Natural Bridges, Utah[c]	141000	1347-1972	0.44	0.33	0.37
23	Dolores, Colorado[a]	286540	1794-1972	0.47	0.23	0.27
24	Mesa Verde, Colorado[b]	532547	1450-1963	0.21	0.58	0.47
25	Bobcat Canyon, Colorado[c]	061099	1390-1971	0.27	0.45	0.42
26	Ditch Canyon, New Mexico[c]	012099	1563-1971	0.52	0.37	0.41
27	Aztec, New Mexico[c]	839100	1542-1970	0.41	0.42	0.47
28	Publito Canyon, New Mexico[c]	071000	1643-1971	0.31	0.51	0.51
29	Spider Rock, Arizona[c]	081000	1598-1971	0.52	0.36	0.41
30	Navajo Mountain, Utah[c]	133099	1469-1971	0.22	0.49	0.41

[a]Tree-ring data collected as part of NSF-sponsored Lake Powell Research Project.

[b]Tree-ring data from the files of the Laboratory of Tree-Ring Research.

[c]Tree-ring data collected as part of a project sponsored by the Advanced Research Projects Agency entitled "Reconstruction of Past Climatic Variability."

[d]Identification number refers to the Laboratory of Tree-Ring Research identification number.

[e]Period of record is the period of years included in the tree-ring series.

[f] R_1 is the autocorrelation coefficient.

[g] MS is the coefficient of mean sensitivity.

[h] SD is the standard deviation.

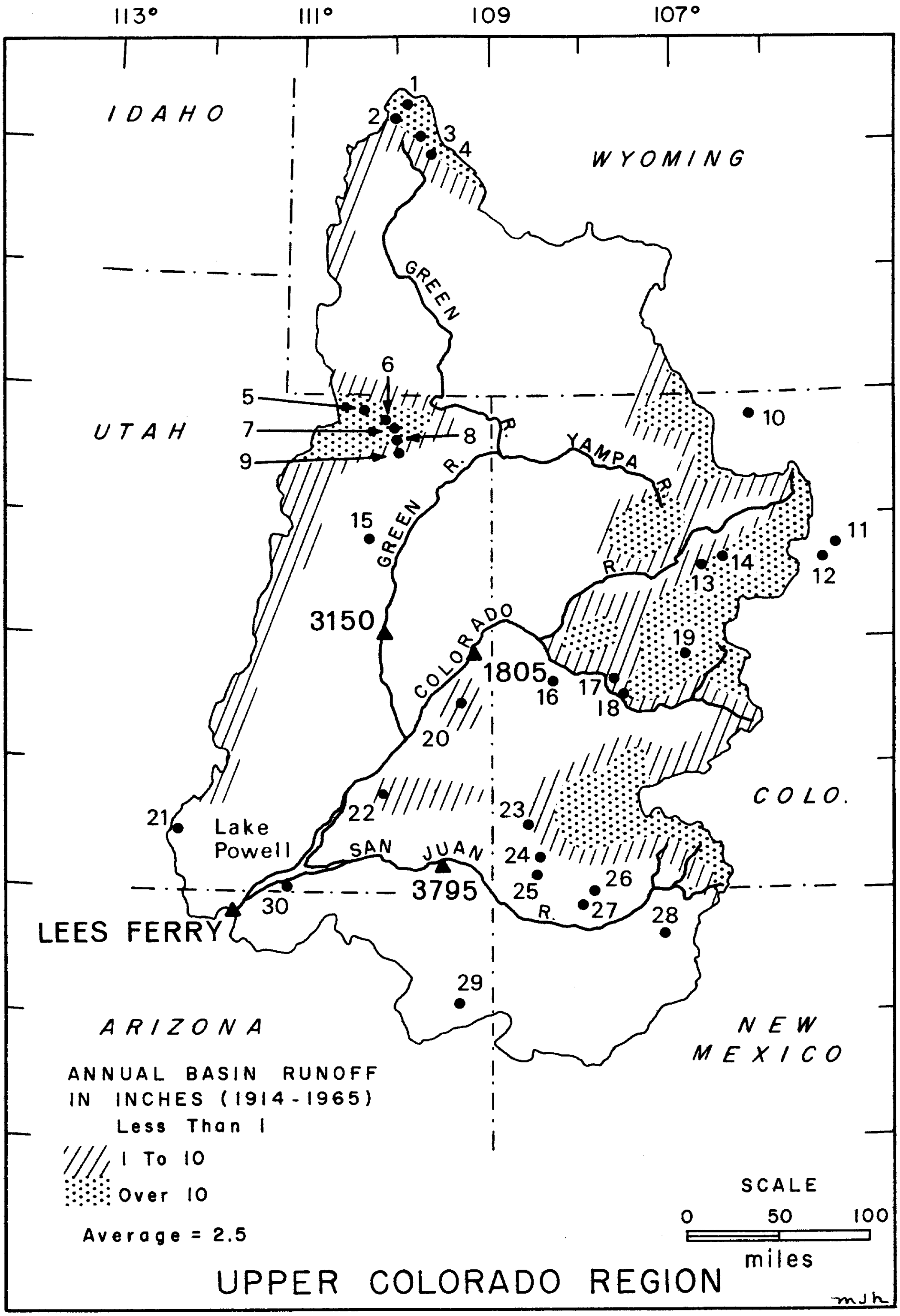

Figure 2: Map of the Upper Colorado River Region Showing (a) Major Runoff-Producing Areas (Shaded); (b) Location of Tree-Ring Data Sites (Dots)--See Table 3 for Names of Numbered Sites; (c) Four Major Gaging Sites (Triangles: 3150--Green River at Green River, Utah; 1805--Colorado River Near Cisco, Utah; 3795--San Juan River Near Bluff, Utah; and Lees Ferry, Arizona.

also the laboratory dating, measuring, and computer processing. Recent evaluations indicate that each new such series costs about $3,000 to collect and process.

All tree-ring data utilized in this study were processed in accordance with the procedures currently in use at the Laboratory of Tree-Ring Research; that is, the individual cores were (1) mounted in wooden core mounts, (2) surfaced to aid in distinguishing the individual rings, and (3) cross-dated. The individual rings were measured to within 0.01 millimeter (0.0004 inch) as described in Stokes and Smiley (1968).

Because most tree-ring data series are, in fact, nonstationary time series (that is, both the mean ring-width and variance are functions of time), each must be transformed to at least a weakly stationary series. This is accomplished by fitting a least-squares-fit curve, most commonly of modified exponential form, to the annual ring-width series. An index is then formed by considering the value of the curve at the time t as the expected value, and by dividing the actual value by the expected value. Although this operation has some drawbacks, it is necessary to transform the original nonstationary series into a more usable stationary one. After all measured radii are transformed into a series of indices, they are averaged into individual tree chronologies, and, subsequently, the tree chronologies are averaged to obtain the mean-value function for the site.

We have chosen from among the 30 tree-ring series used in this study subsets that we feel best reflect the past annual tree-growth which is distributed over the Upper Basin and which is influenced by moisture variations. These ring-width index series are shown in composite in Figure 3. Based on the work of Stockton and Fritts (1971), it is reasonable to infer in this region that the larger ring-width indices are indicative of years of ring growth during which above-normal seasonal precipitation was coupled with below-normal seasonal temperatures. Conversely, one can infer that the narrower rings are indicative of years of ring growth in which the seasonal precipitation was below normal and the seasonal temperature above normal.

Working with the above inferences, one can note several interesting aspects about past climate in various parts of the UCRB. For the period from 1900 through 1964, the most obvious feature of most of the ring-width series is the generally downward trend from a maximum in about 1917. In fact, in many of the series the period of predominantly higher growth (as reflected by larger-than-normal ring-width indices covering the period from 1907 through 1932) is the greatest in both magnitude and duration of any period during the last 450 years. Only occasionally do the ring-width indices exceed the magnitudes of this period and then it is usually only a local phenomenon and is not repeated throughout the other chronologies. It is interesting to note that, as compared with the series to the south, those series north of an east-west line along the crest of the Uinta Mountains do not show as well the pronounced downward trend since about 1917, and they do not in general show the extended period of high growth during the early 1900s. This is suggestive of a long-term climatic regime that is significantly different from that in the more southerly regions of the UCRB. Additional work will be necessary to confirm or reject this hypothesis, but it does agree with the

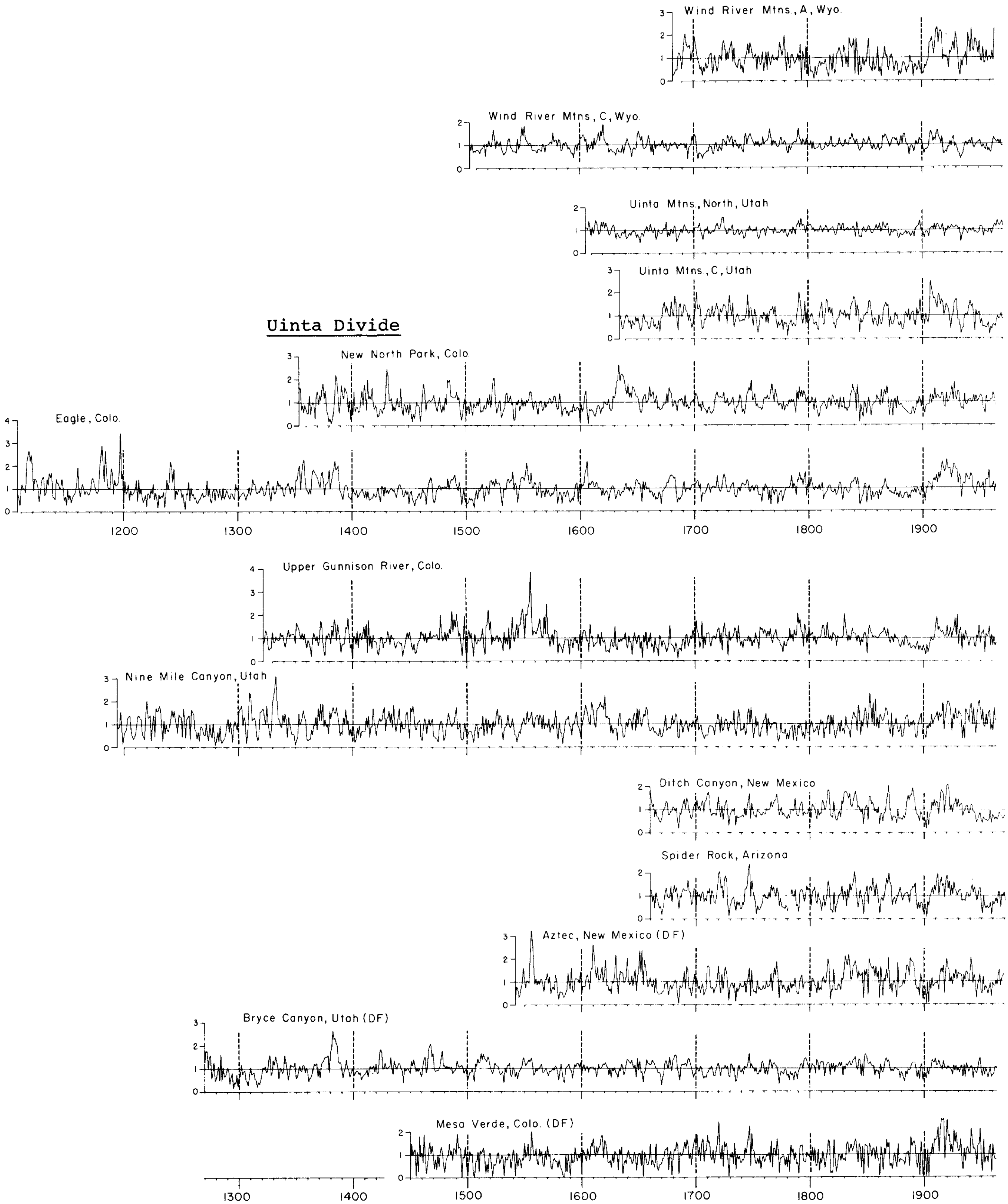

Figure 3: Graphs of a Subset of the 30 Tree-Ring Data Series Shown in Table 3 Selected To Show the Variations in Frequency, Trends, and Synchrony within the Upper Basin.

information presented in Fritts and Cathey (1971).

The period from 1800 through 1900 was also one of climatic contrast in the UCRB. In the Upper Colorado River Main Stem areas, as indicated by the New North Park, Eagle, and Upper Gunnison River chronologies, the period from about 1870 to past 1900 was one of extensive low growth and drought. There is far less evidence of such severe extended drought in the tree-ring data from either the Green River drainage area (except, perhaps, for the Wind River Mountains A chronology) or the San Juan River drainage area. The chronologies from the southern portion of the UCRB shown that the period from about 1840 to 1870 was one of greater growth and above-normal precipitation. During this same time in other parts of the UCRB the growth was near or below normal, which suggests more normal-to-dry climatic conditions. The Wind River Mountains A chronology in Figure 3 shows a dramatic period of low growth during the early 1800s, but this must have been localized because it is either far less evident or nonexistent in the other chronologies.

The period from 1600 through 1700 appears to have been one of above-normal growth and, consequently, above-normal precipitation in the early part which tended towards more normal climatic conditions in the later part, at least in the southern portion of the UCRB. However, toward the northern portion of the UCRB, those chronologies which extend back far enough to cover this time period indicate extensive drought in the early part of the century, extending perhaps through the 1660s in the Uinta Mountains.

During the later part of the period from 1500 through 1600, an extensive drought occurred over most of the UCRB. All the tree-ring data series covering this time period show some evidence of this drought, but the magnitude and duration appear to vary in different parts of the Upper Basin. The longest and most severe drought appears to have occurred in the central portion of the UCRB (Upper Main Stem area). The duration was somewhat reduced in both the northern and southern parts of the Upper Basin region.

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Background

Total annual streamflow records have been reconstructed for various subbasins within the Upper Basin region of the UCRB by utilizing the climatic signal inherent in the tree-ring series selected from the trees in the major runoff-producing areas. The basic technique of reconstruction and the logic behind the use of appropriately chosen tree-ring series have been detailed by Stockton (1975) and will not be repeated here. However, below we will briefly explain the system of models used.

If the climatic input into either the biologic system (represented by the tree-ring series) or the hydrologic system (represented by the runoff series) were purely an annual phenomenon (no year-to-year carryover), the model could represent a simple one-to-one relationship. However, in neither system is such necessarily the case.

Consider first the biologic system, as represented by the tree-ring series. Fritts (1976) illustrates how the tree-ring response to a climatic input can be recorded in ring widths over a number of consecutive years. This is shown, greatly simplified, in Figure 4, where a climatic

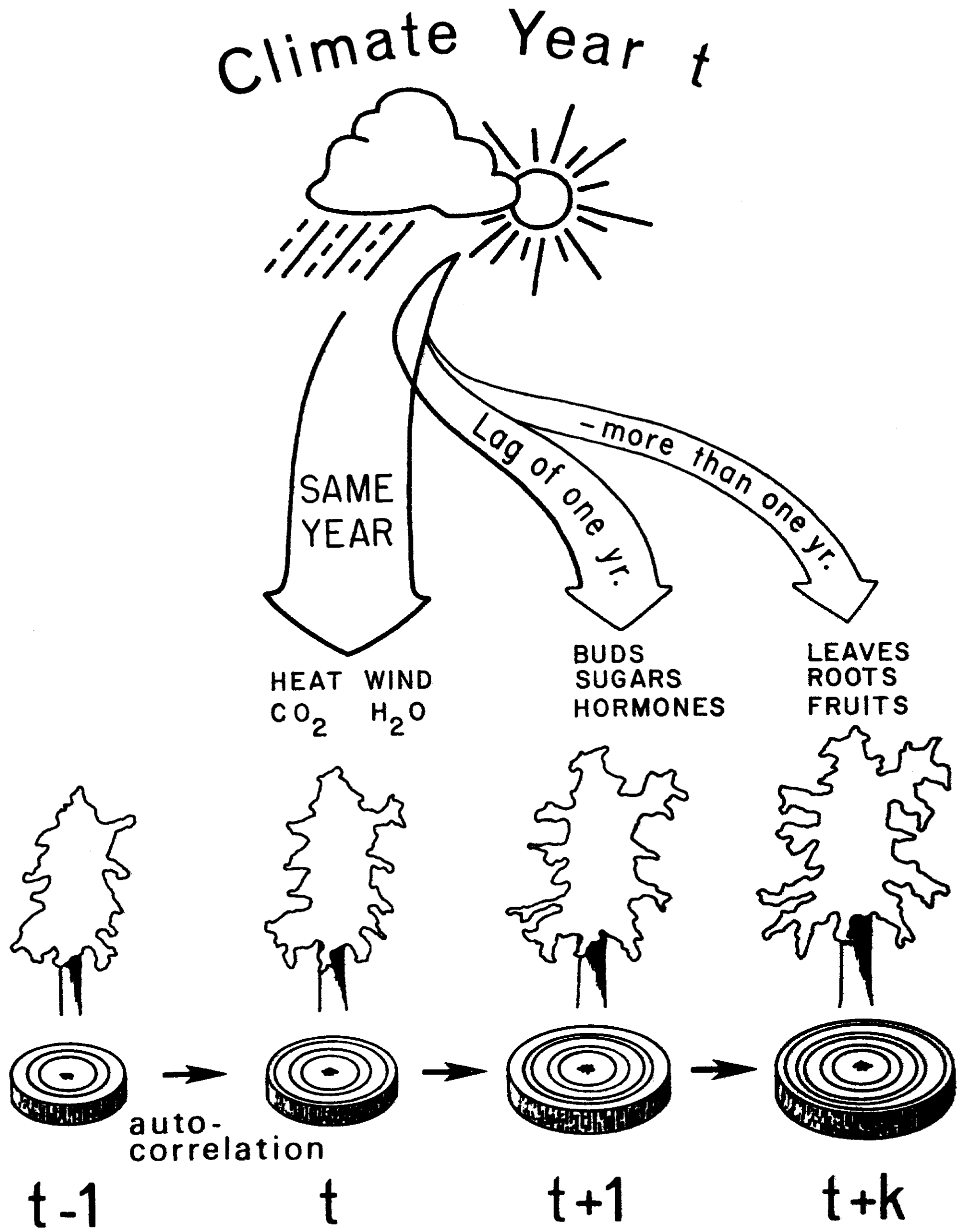

Figure 4: Schematic Diagram Showing How Climate of Year t Can Affect Tree Growth in Year t + k (after Fritts, 1976).

input of precipitation, temperature, and insolation coupled with atmospheric elements of wind and carbon dioxide is reflected in the ring width not only of year t but also of year t + 1 (through bud development and sugar and hormone storage and carryover) and of year t + k (through leaf, root, and fruit growth processes). Superimposed upon this climatic carryover effect is a food storage and soil moisture carryover as reflected in the tendency for rather significant autocorrelation in the ring-width series. This is expressed by the t - k parameters in the models.

The hydrologic system (represented by the surface runoff series) may also evidence a tendency for autocorrelation. This may be a result of ground-water storage being reflected as baseflow, bank storage, evapotranspiration, or other factors. In certain circumstances, this tendency for persistence may be large enough to require its being taken into account in any reconstruction.

We have tested a set of seven empirically chosen models (Table 4) utilizing different values of $t \pm k$ for the tree-ring series and $f - k$ for the runoff series. Each model has been computed for each of the eight subbasins, three main tributaries, and the entire UCRB. For the eight subbasins, gaged (or historic) flow was used to calibrate the tree-ring data. For the three main tributaries and the Lee Ferry flow, estimated virgin runoff was used. In each individual case, we chose what we considered to be the "best" model and used it in the runoff reconstruction process. We chose the "best" model on the basis of the following: (a) amount of variance duplicated in the gaged total-runoff record used for calibration, (b) lack of autocorrelation in the residuals, (c) ability to reproduce independent data (i.e., data not used in the calibration process), (d) capability of the reconstructed series synchronous with the recorded series to duplicate the low-frequency tendencies of the recorded series, and (e) physical reasonableness of the model based upon our knowledge of the tree-ring data, the area from which they were sampled, and the hydrology of the subbasin under consideration. The models chosen for reconstruction and the degree to which these models duplicate the calibration record (correlation coefficient) along with other pertinent data are shown in Table 5.

Table 4: Seven Models for Predicting Annual Runoff Utilizing Tree-Ring Data

Model Number		
1	Runoff (f_t)	tree-ring series x_t, x_{t-1}, x_{t-2}, x_{t-3} with $f_{t-1} + f_{t-2} + f_{t-3}$
2	Runoff (f_t)	tree-ring series x_t, x_{t-1}, x_{t-2}, x_{t-3} with $f_{t-1} + f_{t-2}$
3	Runoff (f_t)	tree-ring series x_t, x_{t-1}, x_{t-2}, x_{t-3} with f_{t-1}
4	Runoff (f_t)	tree-ring series x_t, x_{t-1}, x_{t-2}, x_{t-3}
5	Runoff (f_t)	tree-ring series x_{t+1}, x_t, x_{t-1}, x_{t-2}
6	Runoff (f_t)	tree-ring series x_{t+2}, x_{t+1}, x_t, x_{t-1}
7	Runoff (f_t)	tree-ring series x_{t+3}, x_{t+2}, x_{t+1}, x_t

f_t = annual runoff during year t

x_t = tree-ring data series for year t

Table 5: Tabulation of Gaged USGS Stations for which Tree-Ring Reconstructions of Past Streamflow Have Been Completed. Also shown are the following: (a) numbers of the tree-ring series used in the reconstruction (refer to Figure 2 and Table 3); (b) number of years in the historical record used in the the calibration analysis; (c) correlation coefficient between the gaged record and the tree-ring data; (d) number of years in the reconstructed record (see Appendix for actual records); (e) long-term average flow based on the reconstructed record; (f) long-term standard deviation of the flow based on the reconstructed record; and (g) number of the model (from Table 4) used in the reconstruction process.

Runoff Record Reconstructed	Tree-Ring Sites Utilized in Reconstruction	Number of Years in Calibration Period	Correlation Coefficient	Number of Years in Reconstructed Record	Long-Term Average Flow	Long-Term Standard Deviation in Flow	Model Number
Green River at Green River, Utah	1, 2, 3, 6, 9, 10, 15	57	0.80	392	4.48×10^6	1.43×10^6	6
Green River near Daniel, Wyoming	1, 2	31	0.64	459	3.649×10^5	0.571×10^5	7
New Fork River near Boulder, Wyoming	3, 4	48	0.70	288	2.872×10^5	0.511×10^5	6
Whiterocks River near Whiterocks, Wyoming	6, 7, 8	54	0.76	239	8.871×10^4	2.39×10^4	6
Colorado River near Cisco, Utah	13, 14, 16, 19	49	0.92	323	5.846×10^6	1.532×10^6	6
Fraser River near Winter Park, Colorado	12	51	0.66	252	2.772×10^4	3.392×10^4	4
Taylor River near Almont, Colorado	17, 18, 19	51	0.68	482	2.526×10^5	0.551×10^5	7
Gunnison River near Grand Junction	16, 17, 18, 19	45	0.78	322	2.134×10^6	0.646×10^6	6
Dolores River at Dolores, Colorado	23, 24	44	0.86	161	2.982×10^5	1.063×10^5	5
Colorado River near Cameo, Colorado	13, 14	28	0.79	500	2.823×10^6	0.562×10^6	5
San Juan River near Bluff, Utah	26 (2 species), 28, 29	57	0.85	309	2.20×10^6	0.730×10^6	6
Colorado River at Compact Point (Lee Ferry)	1, 2, 6, 9, 10, 11, 13, 14, 15, 17, 18, 19, 20, 21, 24, 25, 30	50[a] & 65	0.86 & 0.87	450 & 450	13.94×10^6 & 14.20×10^6	3.82×10^6 & 3.54×10^6	6 & 6
Colorado River at Compact Point (Lee Ferry) using data from Upper Colorado Region State-Federal Inter-agency Group (1971) for calibration	1, 2, 9, 13, 14, 15, 17, 18, 19, 20, 22, 24, 25	47[a]	0.91	450	13.06×10^6	3.46×10^6	6
[a]Year-by-year average of these two records				450	13.51×10^6	3.56×10^6	

The empirical results of our analysis indicated that models 4 through 7 were consistently the best models for the reconstruction of streamflow. On the basis of physical reasonableness, there did not seem to be reason to overrule this conclusion. It is significant that these models are the ones which include tree-ring data and do not include prior years of flow.

The individual tree-ring sites within the UCRB used in the reconstructions were not necessarily of equal importance. Consequently, we used a method of spatial and temporal weighting wherein eigenvectors were extracted from a correlation matrix for the suite of tree-ring series to be utilized and for which each was lagged three times. For example, in one of the reconstructions for the Colorado River at Lee Ferry, we used data from 17 tree-ring sites, and when each had been lagged three times, the resulting matrix of data consisted of 68 variables. The resulting eigenvectors were then utilized to weight the original series, and the results were principal components or amplitudes. The resultant weighted value had the desirable property of being orthogonal, and in addition, as long as the variance that the eigenvector accounts for was sufficiently large, the resultant weighting usually was physically reasonable. As the covariance diminished, the eigenvectors were still orthogonal but probably had no physical relationships, as the orthogonality constraint becomes overriding. In all cases, only eigenvectors with corresponding roots greater than 1.00 and accounting for a greater percentage of the variance than would be expected from a matrix of a comparable number of random series were used. In no case were more than 30 eigenvectors used.

The reconstruction equations were established for each model shown in Table 4 by using least-squares analysis, in which the individual orthogonal variables were evaluated before they were entered into the equation. If the F value did not exceed 3.00, the variable was not used in the calibration equation.

The streamflow data used for the reconstruction of the virgin flow at the Compact Point (Lee Ferry) are from the Upper Colorado River Commission (Hely, 1969, p. 49) and the <u>Comprehensive Framework Study</u> (Upper Colorado Region State-Federal Interagency Group, 1971). These figures are the measured flow with estimated Upper Basin depletions restored to it, and they represent the virgin flow at the Colorado River Compact Point, which is one mile downstream from the mouth of the Paria River. There is no gage at this point. The actual flow at the Compact Point is computed as the sum of the Colorado River and the Paria River flows, both at Lees Ferry. The latter flow is measured one-half mile above the mouth. The Compact Point is termed "Lee Ferry" in the Colorado River Compact and other legal documents. Because this is the accounting point between the Upper and Lower Basins, it is extremely important to try to determine the average undepleted or virgin flow at this location.

There has been a recording gage on the Colorado River at Lees Ferry (near the Upper and Lower Basins) since January 19, 1923. From June 13, 1921, to January 19, 1923, reference stakes and staff gages were used to determine flow, and these measurements were referenced to the present gaging site. Prior to June 1921, there was no gaging at Lees Ferry, and the earlier data are based on extrapolations from other records at other stations in the Colorado River Basin. Beginning with the 1914 water-year, figures are available for the three major tributary stations (Green River, San Juan River, and the Main Stem Colorado River), and these figures have been used to estimate the actual flow at Lees Ferry and the Lee Ferry Compact Point. Regression analysis by the authors showed that the flow at Lees Ferry gage can be accurately computed as a function of the three major tributary gages. Thus the total flow data beginning in 1914 are judged to be accurate enough for the calibration of the reconstruction analyses. The year 1914 was used as the starting point for two of the reconstruction analyses (Table 5 and Figure 5).

Streamflow data from 1896 through 1913 are less accurate. This portion of the historical record is based on an extrapolation from more distant and less comprehensive gaging. This longer record also was used in a reconstruction (Table 5 and Figure 5).

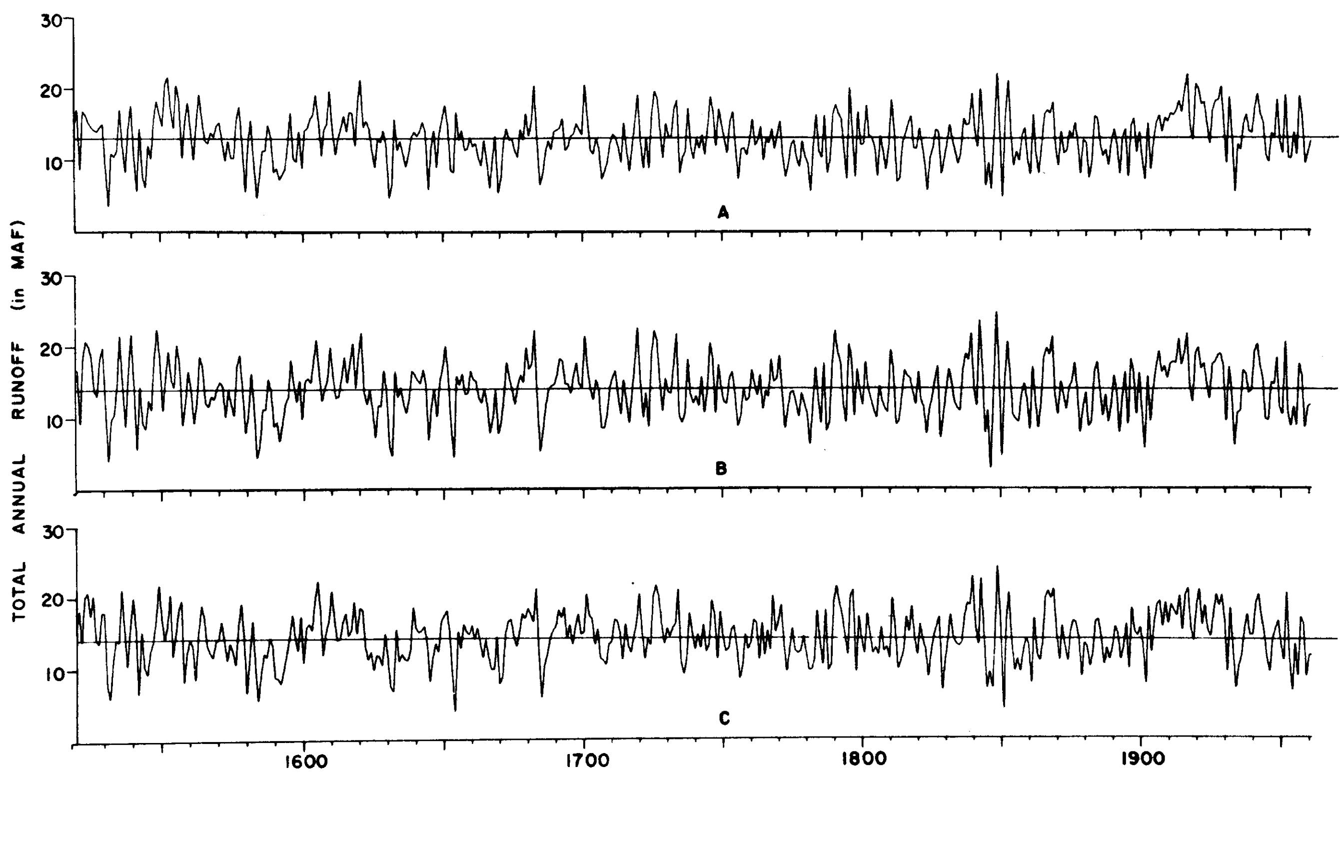

Figure 5: Reconstructed Hydrographs for the Colorado River at Lee Ferry (Compact Point) Based on (a) a 50-Year Calibration Record (Framework I Study Data) and a 13-Station Tree-Ring Data Grid; (b) a 50-Year Calibration Record (Upper Colorado River Commission Data) and 17-Station Data Grid; (c) a 65-Year Calibration Record (Upper Colorado River Commission Data) and 17-Station Tree-Ring Data Grid. (See Table 5 for corresponding tree-ring data series included in each case and Figure 2 for relative locations.)

Estimates of various depletions or consumptive uses pose some serious problems. Extrabasin diversions and changes in reservoir storage can be quantified fairly accurately by at-site measurements. However, evaporation and bank storage determinations at major reservoirs are subject to some uncertainties. Also, other consumptive uses, primarily for irrigation, are not accurately measured in many cases and must be estimated. In 1962 the extrabasin diversions were on the order of 0.5 maf, changes in reservoir storage were several hundred-thousand acre-feet, evaporation and bank storage were less than 0.05 maf, and other consumptive uses were about 2.00 maf for a total of 3.3 maf. With a long-term reconstructed virgin runoff of 13.5 maf, an error of 20 percent in estimated 1962 Upper Basin depletions would be 0.66 maf, or only 5 percent of the reconstructed figure.

Runoff Reconstructions for Lee Ferry, Arizona

We have reconstructed the virgin, or total, annual runoff at Lee Ferry, Arizona (the 1922 Colorado River Compact accounting point), using different models, different tree-ring data grids, and different flow records for calibration (see Table 5, Figure 5, and the Appendix). The models were varied on the basis of percentage variance accounted for in the calibration record, unbiasness in the residuals, and ability to duplicate data not used in the calibration equation. The data used for calibration were from the USGS (Hely, 1969; Table 5, page D-49). The records of actual flow from 1896 through 1913 and the records of virgin flow from 1896 through 1945 were published by the Bureau of Reclamation (U.S. Department of the Interior, 1954; pp. 145-146). Records of virgin flow from 1946 through 1966 were furnished by the Upper Colorado River Commission. Another data source was the Comprehensive Framework Study of the Upper Colorado River Basin (Upper Colorado Region State-Federal Interagency Group, 1971; Table II) and covered the period from 1914 through 1965. Both sets of data represent the estimated virgin outflow from the Upper Basin. The mean and standard deviation of the data from Hely (1969) are 14.65 and 4.47 maf, respectively, for the period 1914 through 1965 (52 years), whereas data from the Comprehensive Framework Study show 14.87 and 4.20 maf, respectively, for the same period. For the 65-year period 1899 through 1963 (data from Hely, 1969), the mean is 15.12 maf and the standard deviation is 4.25 maf. The tree-ring data grids utilized consisted of subsets comprising 13 and 17 tree-ring sites, respectively. The numbers of the sites used in each case are included in Table 5, and the locations of the sites are shown in Figure 2.

The 65-year calibration period includes a portion of the historical record that was estimated from a longer flow record upstream. There is some question as to whether these data should or should not be used in a calibration equation, especially as our study indicates significant variations in flow for different areas of the UCRB. However, the longer record does include some of the larger flow years which are desirable for inclusion in the calibration equation. To check the reliability of the 65-year calibration equation, we computed another equation using only 50 years of data (1914 through 1963) and compared the reconstructive qualities with the published data covering the period 1896 through 1913. The reconstruction equations are as follows:

For 65-year calibration period:

$$f_t = 14.15 - 0.589E_1 - 0.549E_2 - 0.753E_3 - 0.634E_5 - 0.831E_{10} - 0.778E_{15} + 0.542E_{22} - 0.849E_{27} + 0.844E_{29} \quad (1)$$

where

f_t = reconstructed total annual runoff for year t

E_i = ith principal component from appropriate tree-ring data grid

The above accounts for 75 percent of the variance in the calibration record.

For 50-year calibration period:

$$f_t = 13.94 - 0.616E_1 - 0.781E_2 - 0.889E_3 - 0.701E_5 - 0.641E_{10} - 0.992E_{15} \quad (2)$$

This equation accounts for 78 percent of the variance in the 50-year calibration record.

The six variables entered into equation (2) are the same as the first six entered into equation (1). However, the relative weights vary by as much as 36 percent, and more variance is accounted for by equation (2) which has three less variables.

Utilizing data from the Comprehensive Framework Study and a slightly modified tree-ring data grid (see Table 5), the reconstruction equation becomes

$$f_t = 13.06 - 0.596E_1 - 0.506E_2 - 1.055E_3 - 0.508E_4 + 0.468E_7 - 0.573E_{11} \quad (3)$$

This accounts for 87 percent of the variance in the calibration record.

The yearly respective means for long-term virgin flow are 14.15 maf for the 65-year calibration, 13.94 maf for the 50-year calibration, and 13.06 maf for the Comprehensive Framework Study calibration.

Figure 6 illustrates how equation (1) duplicates the estimated total streamflow data for the period 1896 through 1913 (which was part of its calibration period) as compared to equations (2) and (3). As one would expect, the equation calibrated by including this period has a mean that is closer to the mean for this period of 18 years, even though the equation explains less of the variance of the whole calibration period. The extension of the streamflow record back through this 18-year period is based mainly on data from the region where the wet period of the early 1900s began sooner than it did in the rest of the UCRB. Therefore, it is likely that this estimated flow record may be biased toward the high side.

The yearly mean of the estimated record for this 18-year period is 15.80 maf and the standard deviation is 3.87 maf. Equation (1) gives a yearly mean of 15.6 maf and a standard deviation of 3.3 maf, whereas equation (2) gives a yearly mean of 14.65 maf and a standard deviation of 3.85 maf. The overall reconstructions seem to be unbiased, in that for equation (1) the reconstructed values both exceed the estimated values nine times and are less nine times. For equation (2) the reconstructed values exceed the estimated values eight times and are less ten times. From equation (3), the resultant yearly mean is 13.5 maf and the standard deviation is 3.4 maf; both are considerably less than are those for the estimated data and for equations (1) and (2). When compared to the independent data for the period from 1896 through 1913 (Figure 6),

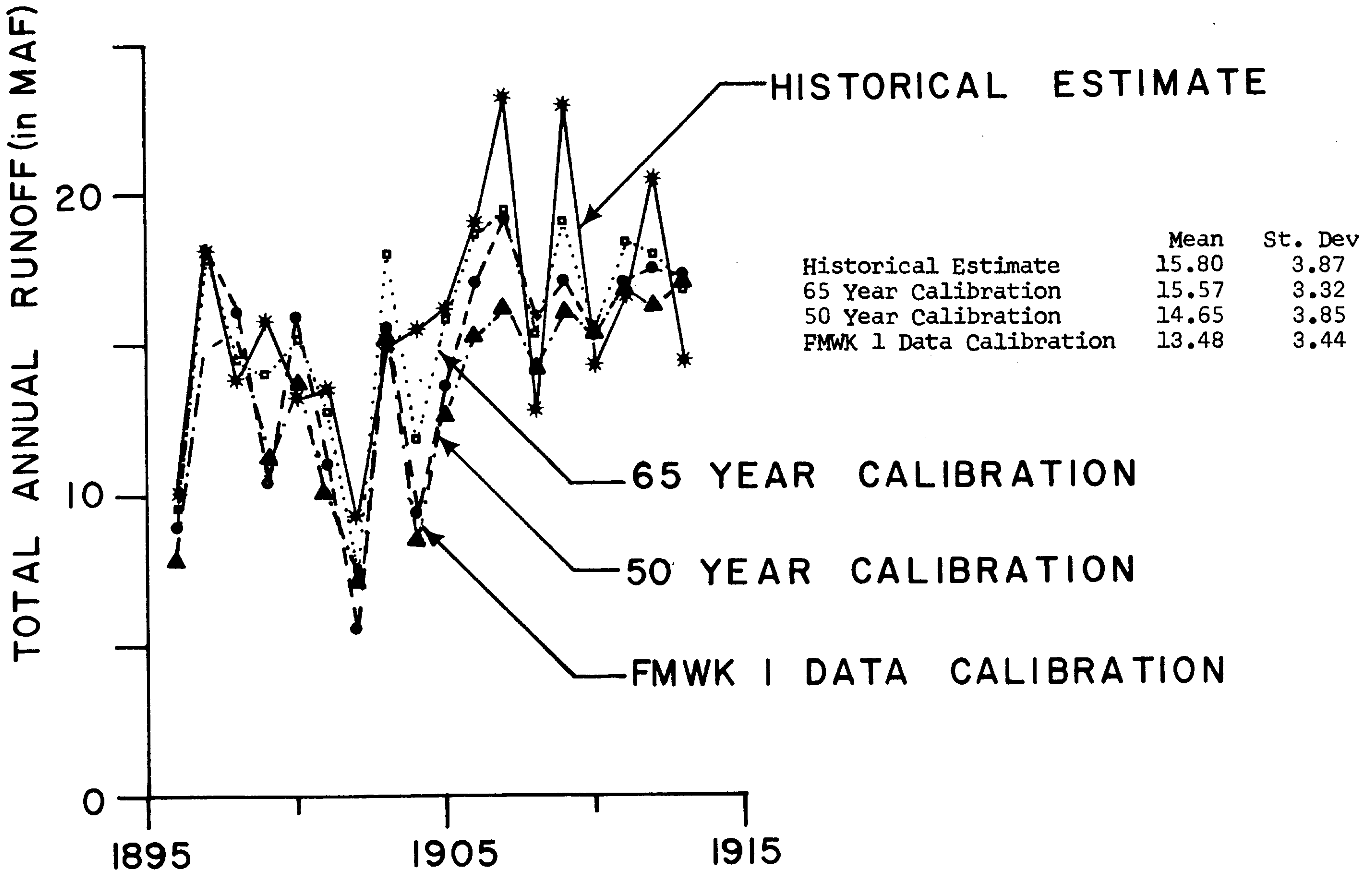

Figure 6: Comparison of the Historical Estimate of Flow at Lee Ferry with That Estimated by Tree-Ring Data Using a 65-Year Calibration Equation (Equation 1), a 50-Year Calibration Equation (Equation 2), and the Framework I Data Calibration Equation (Equation3). (It must be emphasized that these are means for the 19-year period only and not longer term mean values.)

a tendency is seen for slight biasness in underestimation with respect to this particular data set, since for the 18 years there are 11 underestimates and 7 overestimates.

The autocorrelation structure in all three cases appears to be quite similar, with the first-order autocorrelation being approximately 0.33. We have not yet analyzed the structure of the autocorrelation, but judging from the correlograms (Figure 7), it is more complex than that of a simple autoregressive model and probably has a mixed autoregressive moving average.

We have not yet computed the variance spectra (i.e., the distribution of variance with respect to frequency) for any of the three reconstructions included here. For an earlier version of a reconstruction which would be similar to those above and which is based on data from Hely (1969), Stockton (1975) computed variance spectra for the tree-ring reconstructed data, the historically gaged data for the period 1896 through 1961, and the long-term tree-ring data reconstructed record for the period 1564 through 1961. Figure 8 illustrates the fidelity with which the tree-ring data duplicate the frequency distribution in the gaged record. One would

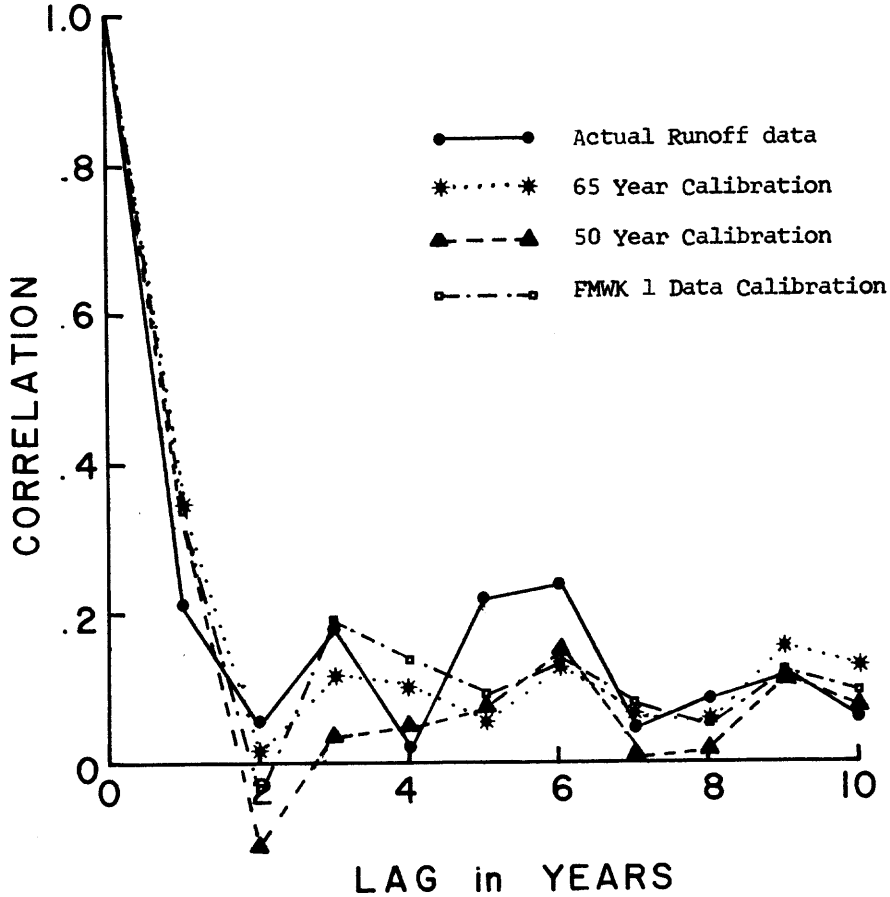

Figure 7: Comparative Correlograms for the Three Reconstructed Records of Flow of the Colorado River at Lee Ferry and the Gaged Record.

expect a similar degree of comparison if any of the three reconstructions included here were similarly analyzed. Figure 9 shows the distribution of variance with respect to frequency in the long-term reconstructed record. Again, one would anticipate a similar type of spectrum from any of the three reconstructions above.

Figures 8 and 9 illustrate two important points. First, utilizing our techniques for reconstructing UCRB runoff from tree-ring data, we were able to duplicate very well the distribution of variance with respect to frequency in the gaged record. Second, the long-term spectrum (Figure 9) shows considerably more evidence of long-term variation in flow than exists in the gaged record (Figure 8). This reinforces the concept that the length of record for the gaged series is inadequate.

A critical question is which of the three reconstructions of past runoff at Lee Ferry is the best. Our reasoning is as follows. The reconstruction based on the 65-year calibration record (equation 1) includes data from the 18-year estimated record (1896 through 1913) that are

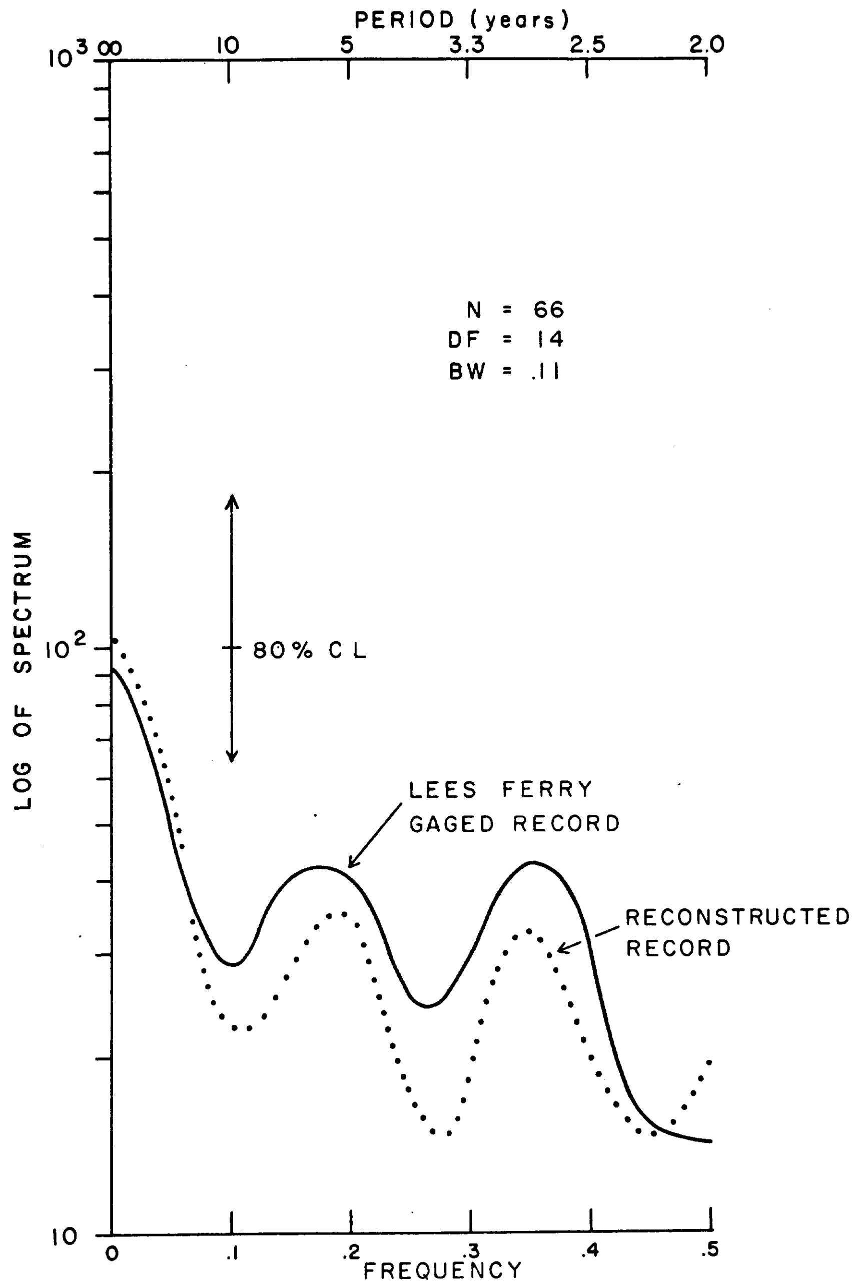

Figure 8: Autospectra for the Gaged Record at Lee Ferry versus that for the Same Period (1896-1961), but Reconstructed Using Tree-Rings. (This figure demonstrates the fidelity with which the tree-ring data duplicate the variance of the gaged data over the entire frequency range, after Stockton, 1975.)

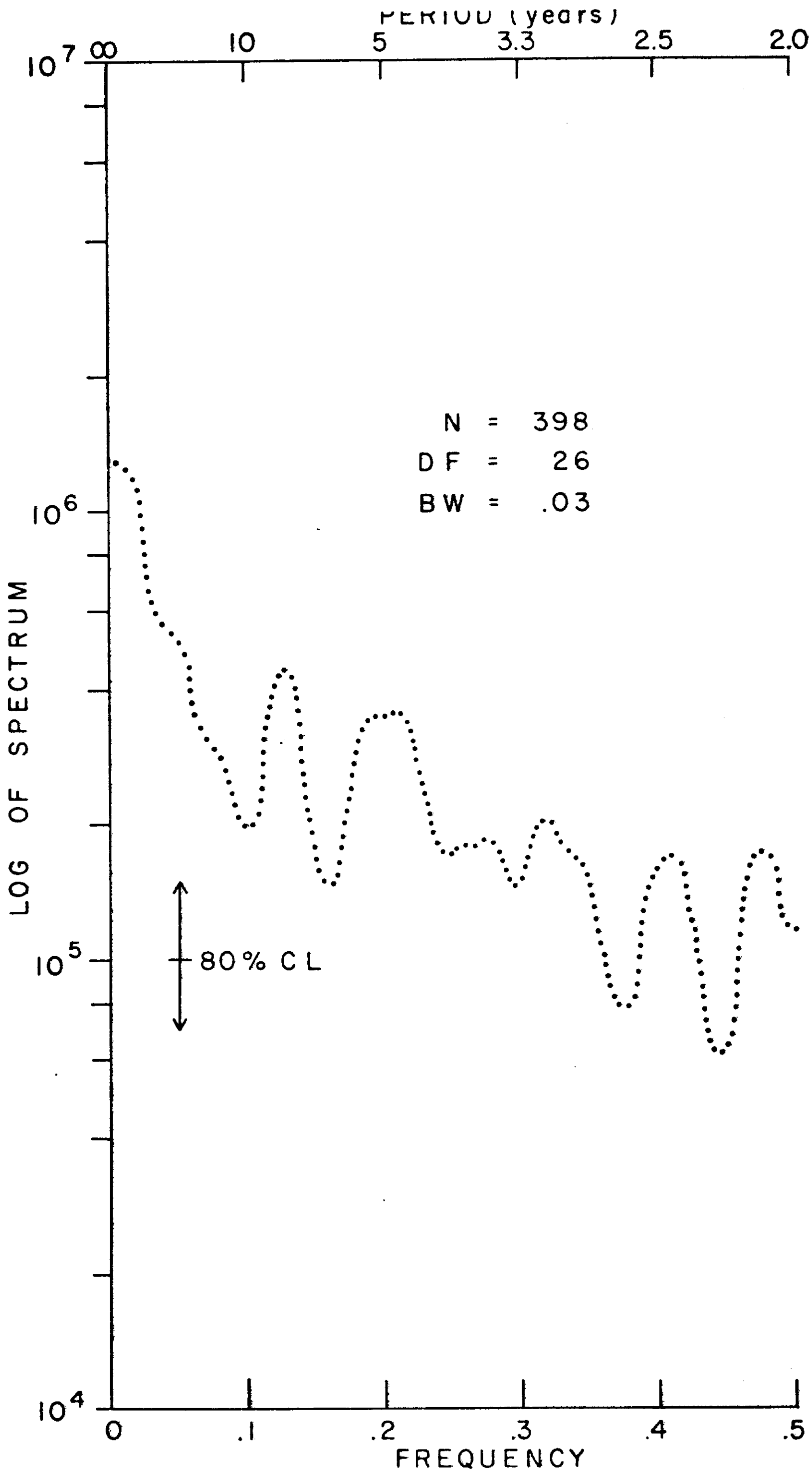

Figure 9: Autospectrum of Long-Term Lee Ferry Record Reconstructed from Tree-Ring Data for the Period 1564-1961 (after Stockton, 1975).

questionable for calibration purposes and for previously stated reasons are probably biased toward the high side. The reconstruction based on the 50-year calibration (equation 2) does not contain the drawback of equation (1), but when a slightly different tree-ring grid and calibration data are used from the Comprehensive Framework Study, which is the most recent (1971) evaluation of virgin runoff (equation 3), a slightly different reconstruction is obtained. Therefore, we feel that the best estimate of the long-term reconstruction is an average of the results of equations (2) and (3)--13.94 maf per year and 13.06 maf per year, respectively. Consequently, we arrive at an estimated mean annual runoff of 13.5 maf, ± 0.5 maf, and a reconstructed long-term hydrograph as shown in Figure 10.

Runoff Reconstructions for Subdivisions

For purposes of comparison among subbasins, we divided the Upper Basin into the traditional tributary subdivisions of the Green River above Green River, Utah; the Colorado Main Stem above Cisco, Utah; and the San Juan River above Mexican Hat, Utah. This division allowed assessment of any preferred mode of occurrence of either high or low flows. In Table 5 are listed the following: (a) individual reconstructed records from each subbasin, (b) tree-ring sites used for the reconstruction, (c) number of years in the calibration period, (d) predominant correlation coefficient for comparison of the tree-ring data and the runoff series, (e) number of years in the reconstructed record, (f) long-term average flow as interpreted from the reconstructed record, (g) the long-term standard deviation, and (h) the model number utilized in the reconstructed record (see Table 4 for model descriptions). Some of the records utilized in the streamflow reconstructions for the smaller basins were based on unadjusted historical runoff records; consequently, the mean annual flow figures are

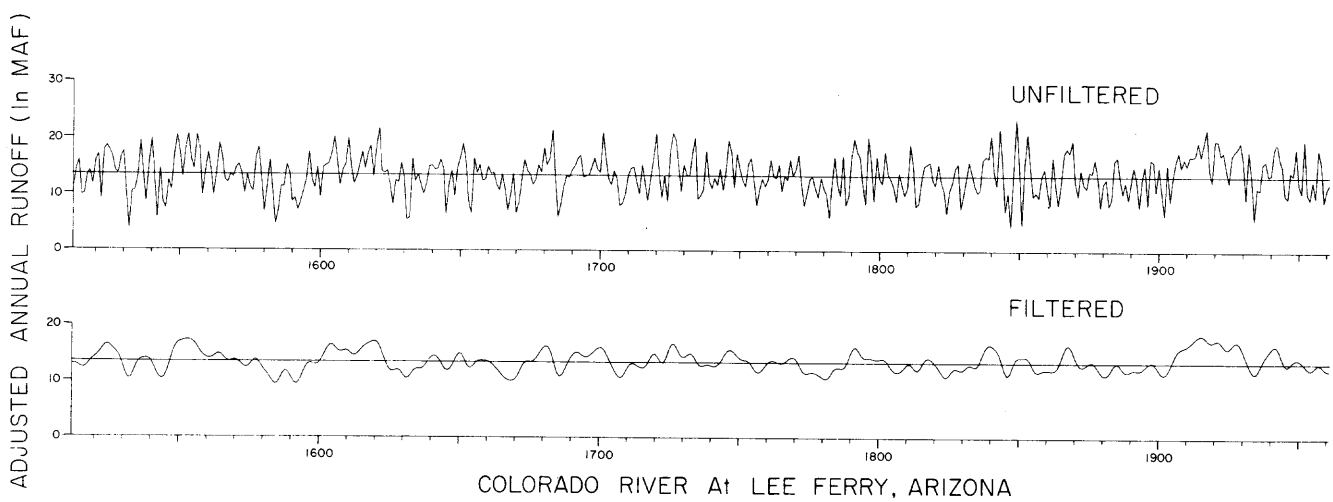

Figure 10: Best Estimate of the Long-Term Hydrograph of Annual Runoff at the Compact Point Based on an Average of the Results of Equations (2) and (3). (The upper graph shows the actual year-by-year values; the lower graph is the same data, but with the high-frequency components--those with a period less than 10 years--removed.)

probably slightly low. For most of the smaller basins, it is unlikely that the mean is substantially affected, because most of the smaller stations chosen for reconstruction were picked partly on the basis of lack of upstream diversions. For the three major tributary subdivisions, estimates of all consumptive uses were obtained and were added back to the historic flow to produce virgin flow figures for calibration of the tree-ring information.

The Green River Basin

Within the Green River Basin, four reconstructions were made at the following gaging stations: Green River at Green River, Utah; Green River near Daniel, Wyoming; New Fork River near Boulder, Wyoming; and Whiterocks River near Whiterocks, Utah. These gaging stations were chosen for reconstruction because of (1) their fairly long, homogeneous historical records which provided a reliable base for calibration, (2) their location relative to existing or potential dendrochronologic sites, and (3) their location within known high-runoff-producing areas.

Plots of the reconstructed records and their comparison show some interesting aspects. In general, the northernmost records (that is, those from the Green River near Daniel, and the New Fork River near Boulder, Wyoming) do not show the pronounced low-frequency variations that are exhibited by the Whiterocks River reconstruction or the Green River reconstruction at Green River. Of specific note is the fact that the reconstructions for the Green (near Daniel) and the New Fork do not show a pronounced downward trend since the early 1900s nor do they show the pronounced high-flow period during the early 1900s. None of the three indicates the pronounced low-flow period during the period from 1870 through 1890. However, the reconstruction for the whole Green River (Figure 11) shows a very pronounced low-flow period during that same time, but the reconstruction includes three tree-ring series from sites in the

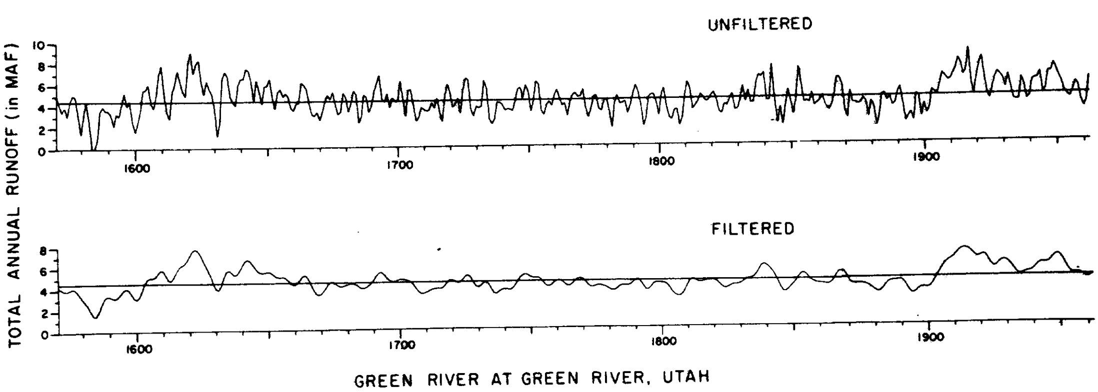

Figure 11: Reconstructed Hydrograph for Total Annual Runoff for the Green River at Green River, Utah. (The upper graph shows the unfiltered data; the lower graph is the same data, but with the high-frequency components--those with a period less than 10 years--removed.)

southern part of the Green River Basin that are not utilized in any of the smaller northernmost subbasin reconstructions. This phenomenon appears to indicate that (1) the northernmost portion of the Green River drainage is affected by climatic trends which differ from those of the southerly part of the Green River Basin and probably the rest of the UCRB, (2) the Whiterocks reconstruction shows some of the same low-frequency components as those of the northern part of the UCRB, and also some characteristics of the southerly part, and (3) the Green River reconstruction at Green River, Utah, shows low-frequency variations that are quite different from those of the northerly part of the UCRB and also of the Uinta Mountains. Specifically, the drought of the late 1800s, the wet period from 1907 through 1932, and the overall downward trend since 1932 are all more pronounced.

With the exception of the reconstructions for the New Fork River (where the long-term average is 287,000 acre-feet per year compared to that for the gaged 39-year record of 284,000 acre-feet per year) and the Green River near Daniel, Wyoming (where the 39-year average of gaged value is 366,000 acre-feet per year versus 385,000 acre-feet per year for the reconstructed record), the long-term runoff values from the reconstructed records are less than those for the gaged records. For the Green River at Green River, Utah (Figure 11), the 50-year total flow record is 4,614,000 acre-feet per year, whereas the reconstructed 392-year value is 4,480,000 acre-feet per year. The Whiterocks River average for 63 years of gaged data is 90,560 acre-feet per year, and that for the reconstructed record is 88,700 acre-feet per year. It seems apparent that the large-scale fluctuations in the southerly portion of the UCRB, particularly the abnormally high runoff in the early 1900s and the no-analogy drought periods such as occurred in the late 1800s may have caused the mean annual runoff figures (which are estimated from the historical record) to be inflated. In records from the northerly part of the UCRB, where these anomalies do not exist, the long-term reconstructed means seem to be slightly greater than those for the measured flow. One could conclude that the anomalous wet period in the early 1900s did not affect the northernmost portion of the Green River Basin and therefore did not inflate the historic means. However, it must be kept in mind that the differences are small in this Basin and should not be overemphasized, although the pattern is worth noting.

<u>The Colorado Main Stem Above Cisco, Utah</u>

Within the subbasin drained by the Upper Colorado River Main Stem above the gaging station at Cisco, Utah, we have reconstructed six station records. The reconstructed record at Cisco (Figure 12) incorporates the long-term trends for both the Upper Main Stem and the Gunnison River tributaries and shows predominantly high-flow years during the period from 1916 through 1932 that were preceded by a prolonged period of predominantly low flow, from about 1873 through 1912. The long-term mean annual flow is 5.86 maf, as opposed to 6.84 maf for the 50-year adjusted historical, or virgin, flow record (1914-1962). Apparently, data from the anomalously high-flow years during the 1920s tend to inflate the mean to above the value that the reconstructed long-term data indicate. Those years are the largest block of continuously high-flow years in the entire 323-year reconstructed record.

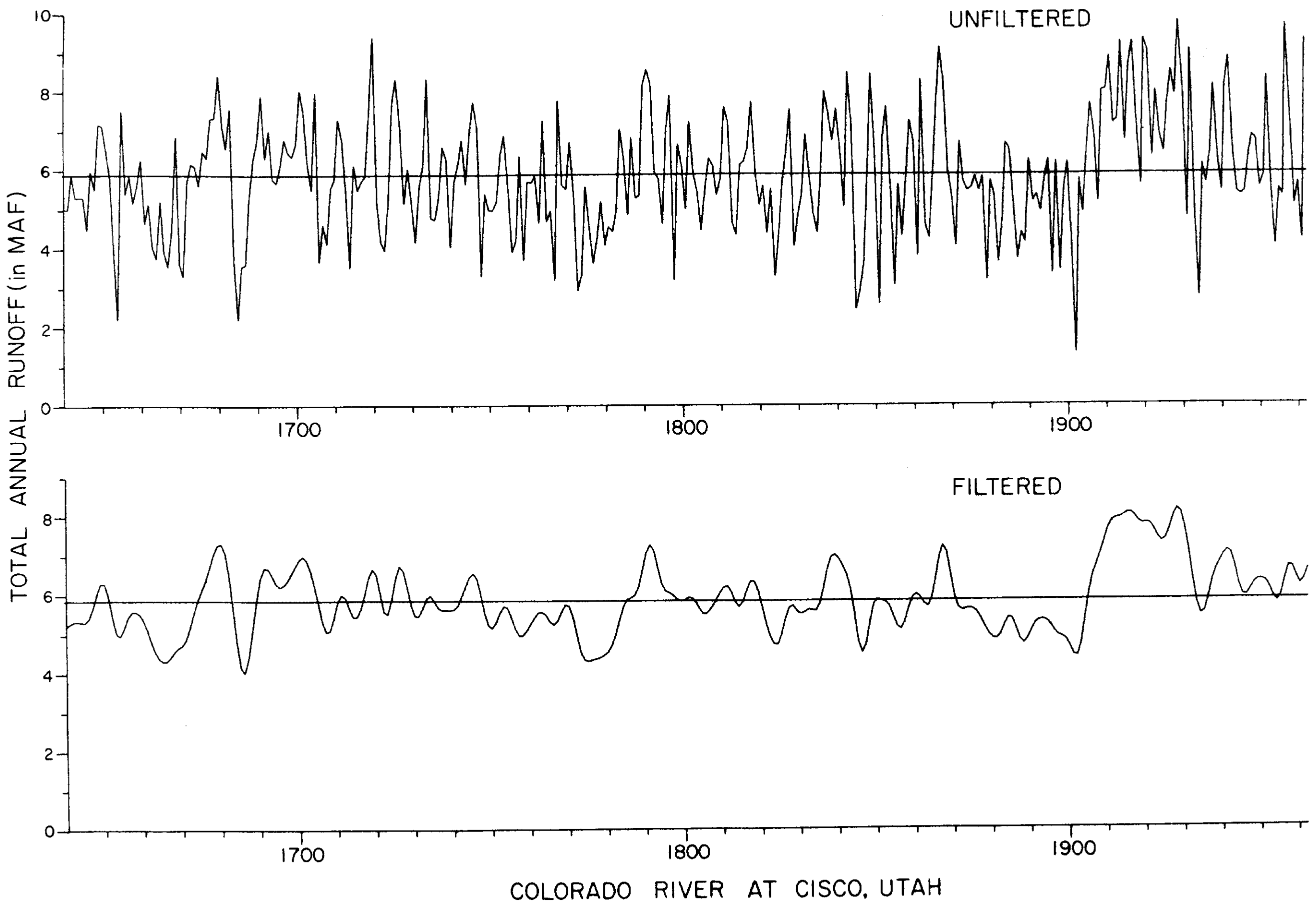

Figure 12: Reconstructed Hydrograph for the Total Annual Runoff, or Virgin Flow, for the Colorado River Near Cisco, Utah. (The upper graph shows the unfiltered data; the lower graph is the same data but with the high-frequency components--those with a period less than 10 years--removed.)

The long-term annual mean for the reconstructed record of the Colorado River at Cameo, Colorado, is 2.82 maf, whereas that for the historically gaged record is 2.78 maf. This annual mean is affected by the presence of transmountain diversions, storage reservoirs, power developments, and irrigation diversions, factors which, due to the absence of their influence in the calibrated record, may be responsible for a lack of long-term variation in the reconstructed record. The reconstruction for the Fraser River near Winter Park, Colorado, differs significantly from the other reconstructions in that it does not show the extended period of drought during the late 1800s. The long-term mean annual runoff for the reconstructed record for the Fraser River is 27,700 acre-feet, as opposed to about 29,000 acre-feet for the gaged record.

Both of the long-term reconstructed records for the Gunnison River near Grand Junction, Colorado, and the Taylor River near Almont, Colorado, show a large block of persistently high-flow years during the period from 1907 through 1932. Each record shows this period as being preceded by a large block of persistent low-flow years during the period from 1870 through 1900. Equally important, however, is the evidence of earlier periods of comparable prolonged high-flow years. The long-term mean annual flow for the Taylor River is 252,600 acre-feet, as opposed to 246,300 acre-feet for the gaged record; that for the Gunnison River near Grand Junction, Colorado, is 2.13 maf, as compared to 1.86 maf for the 62-year gaged record.

The reconstructed record for the Dolores River at Dolores, Colorado, shows a long-term annual mean of 298,000 acre-feet and a gaged record of 311,000 acre-feet.

The San Juan River

Due to the lack of an adequate number of good tree-ring data sites within the San Juan River drainage, only one reconstruction was attempted in this basin--that for the record on the San Juan River at Mexican Hat, Utah. (The USGS gage is termed "San Juan River near Bluff.") This reconstructed streamflow record shows the large high-flow period during the period from 1907 through 1932 as being the longest sustained period of predominantly high flow during the last 360 years. The mean annual flow for the reconstructed record is 2.20 maf, as opposed to 1.89 maf for the adjusted historical, or virgin, flow record. Figure 13 shows the hydrograph for the reconstructed flow at this station.

Comparison of the Green River, Upper Main Stem Colorado River, and San Juan River Reconstructions

We have previously pointed out the long-term flow characteristics of some of the smaller watersheds. It is also important to investigate the significance of these on the larger subbasin runoff. For this reason, we have compared the sample variance spectra and squared

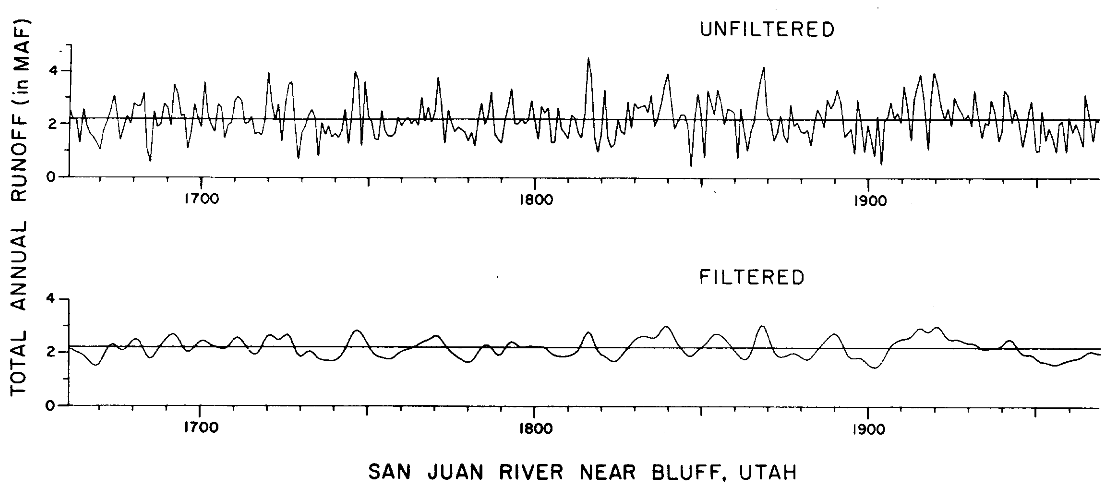

Figure 13: Reconstructed Hydrograph for the Total Annual Runoff for the San Juan River near Bluff, Utah. (The upper graph shows the unfiltered data; the lower graph is the same data but with the high-frequency components--those with a period less than 10 years--removed.)

coherency spectra for the Green River at Green River, Utah; the Colorado River near Cisco, Utah; and the San Juan River near Bluff, Utah.

The sample variance spectra are shown in Figure 14. From these comparisons, one is able to see how similarly the variance is distributed, with respect to frequency, for both the San Juan River and the Colorado Main Stem. The general distribution is amazingly similar, with that for the Colorado River near Cisco being consistently and uniformly greater, over the entire frequency range, than that for the San Juan River. However, the Green River spectrum is concentrated on the low-frequency end and steadily decreases as it approaches the high-frequency end. Consequently, it is obvious that the Green River reconstruction contains considerably more low-frequency variation than do either of the runoff series for the San Juan River or the Colorado River above Cisco, Utah.

The squared coherency spectra show how the individual series are co-varying

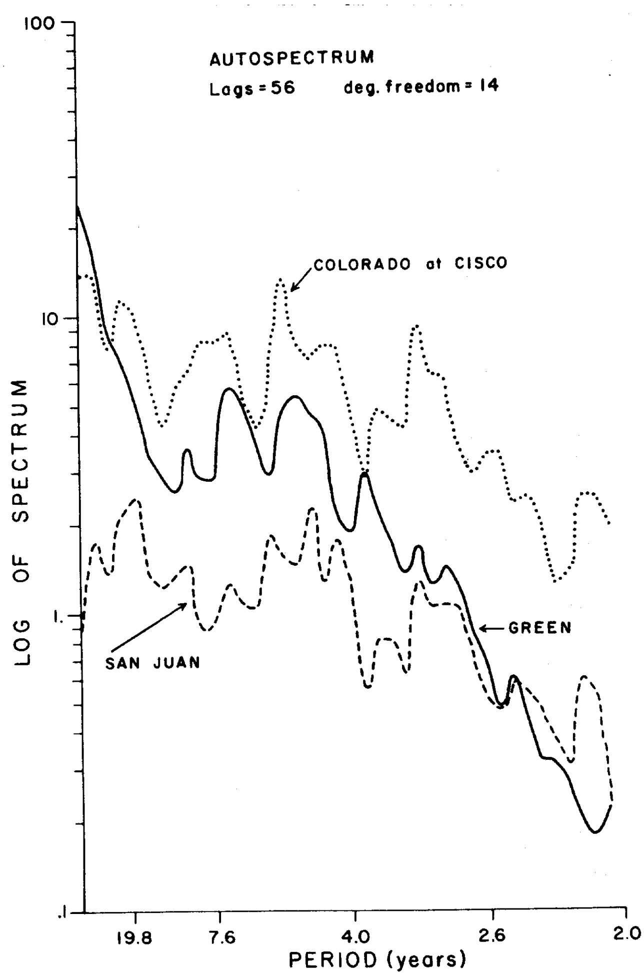

Figure 14: Comparison of the Sample Autospectral Functions for the Long-Term Reconstructed Runoff Records for the Green River at Green River, Utah; the Colorado River Near Cisco, Utah (Colorado Main Stem); and the San Juan River Near Bluff, Utah.

in time and can be thought of as the square of the correlation coefficient defined at each frequency. The squared coherency spectra for the San Juan River and the Colorado River near Cisco (Figure 15A) show a fairly even distribution across the entire frequency range, with perhaps a slightly higher average in the range from 4.5 to 2.0 years. The highest coherency is shown in the frequency range from about 8 to 2.5 years in the comparison of the Green River runoff series with that of the Colorado River near Cisco (Figure 15B). The average coherency squared is about 0.35, but it decreases from the low-frequency range to the high. It appears that although the comparision of the sample autospectral functions (Figure 14) reveals that the variance of the San Juan and Colorado Rivers is distributed similarly with respect to frequency (that of the Green River is quite different), the squared coherency spectra show that the Green and Colorado Rivers co-vary more similarly than do the Green and San Juan Rivers (Figure 15C) or the Colorado and San Juan Rivers. In none of the three cases is the coherency very large over the entire frequency range; it ranges from an average of about 0.35 to about 0.20.

By using the filtered series, the low-frequency variation is accentuated, and it is easier to visually compare the time series. These series are shown in Figure 16. The comparison of the filtered series shows some interesting similarities and dissimilarities among the reconstructions of long-term past flow. All three reconstructions show the predominant downward trend from 1932 to 1961. The flow of the San Juan River was below the long-term mean from about 1945 to 1968. The Colorado River (above Cisco) also shows this prolonged period of below-normal flow, with the exception of two short periods during the late 1940s to early 1950s and the late 1950s, during

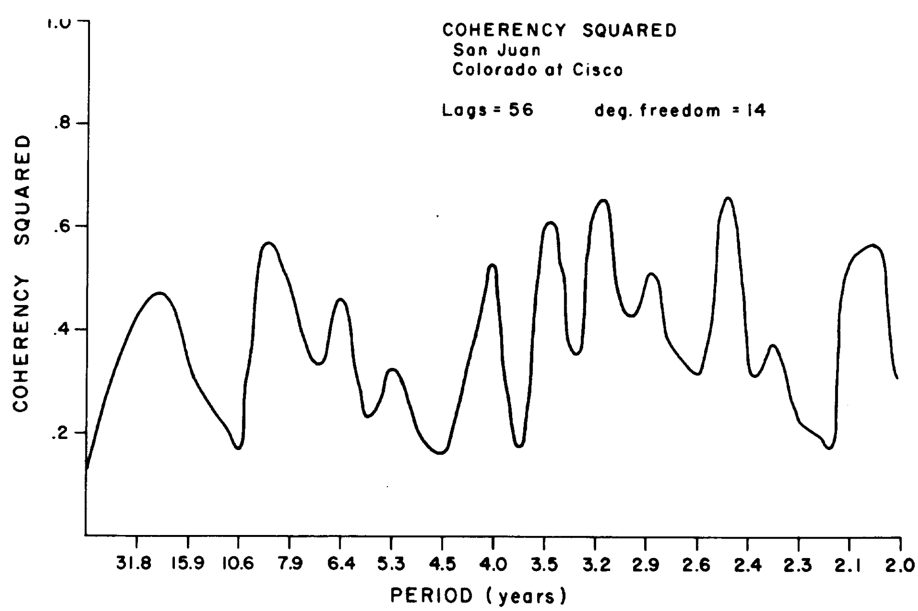

Figure 15A: Squared Coherency Spectra for Long-Term Reconstructed Runoff Records Showing Coherence Between the Reconstructions for the San Juan and Colorado Rivers.

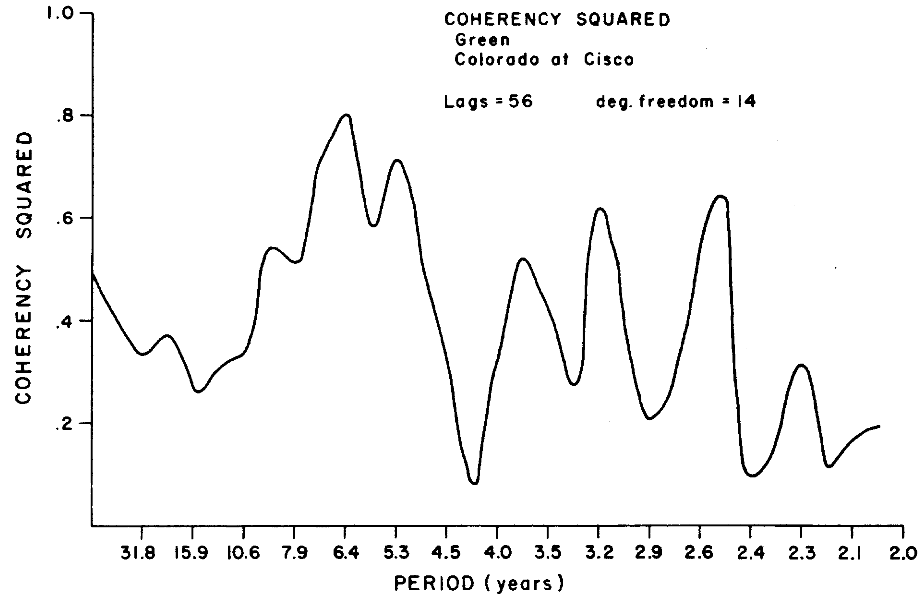

Figure 15B: Squared Coherency Spectra for Long-Term Reconstructed Runoff Records Showing Coherence Between the Reconstructions for the Green and Colorado Rivers.

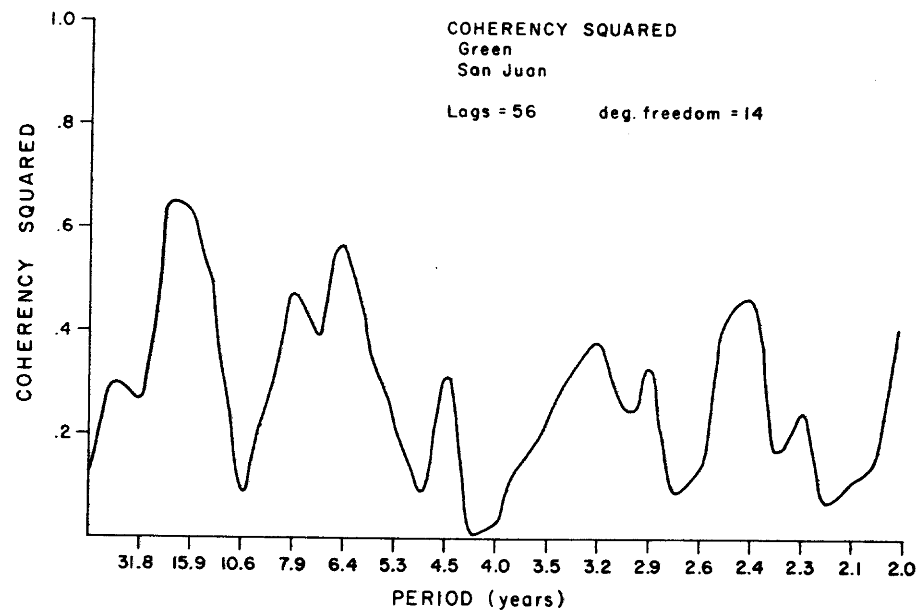

Figure 15C: Squared Coherency Spectra for Long-Term Reconstructed Runoff Records Showing Coherence Between the Reconstructions for the Green and San Juan Rivers.

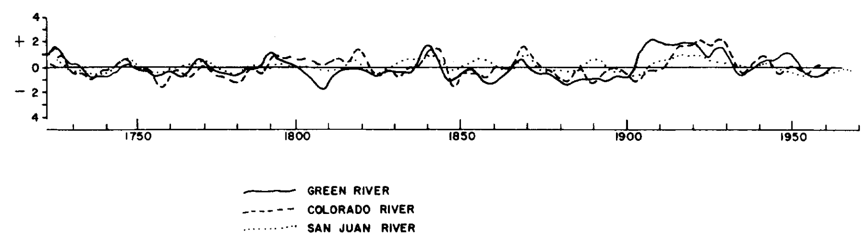

Figure 16: Comparison of Filtered Runoff Series for the Green River at Green River, Utah; the Colorado River near Cisco, Utah; and the San Juan River near Bluff, Utah. (The units on the ordinate are deviations from the mean in millions of acre-feet. By comparing the filtered series, the long-term variation is better displayed.)

which the flow was above normal. The Green River reconstruction above Green River, Utah, shows below-normal flows during the period from 1954 through 1961. Thus, all three major tributaries reflect a tendency toward below-normal flow beginning as early as 1945 in the San Juan River and as late as 1954 in the Green River.

All three major UCRB tributary streamflow records show a pronounced wet period during the early portion of the twentieth century, and in each case this wet period is the longest continuous period of high-flow years in the entire reconstructed hydrograph. All three also show this extended wet period ending about 1933, but the date when the high flows were initiated varies from 1903 for the Green River to 1907 for the San Juan River to 1911 for the Colorado River. None of the three records shows evidence of a severe extended low-flow period during the midwestern drought of the 1930s.

In all three cases, the period prior to this extended wet period was a long one of predominantly low flow. It appears to have been most severe in the Green River Basin and was interrupted by an above-average flow period from 1885 through 1894 on the San Juan River. No analogous long-duration low-flow periods have occurred since the beginning of the historically gaged records.

As is readily seen in Figure 16, there are periods during which the runoff from all three subbasins appears to have been in synchrony, but there are also other periods when records from one or the other did not agree with the third. Although not shown in Figure 16, of particular interest is the period from 1685 through 1735, when a period of high sustained flow occurred on the Green and San Juan Rivers but not on the Upper Main Stem Colorado. This is the only period in the reconstructed record that is at all comparable to the high-flow years of the early 1900s, and it apparently then only occurred in the San Juan and Green River Basins. Also of special interest is the severe extended low-flow period on the Green River from 1578 through 1605. There is no other period of such severe drought in the reconstructed record. Unfortunately, the other two reconstructed records do not go back as far in time and do not cover this time period, so it is not possible to tell if this particular period was as severe and prolonged in the other two basins.

SUMMARY

Review

We have completed long-term reconstructions from tree-ring data of total annual flow for 12 different gaging stations within the UCRB. On a short-term basis, our tree-ring reconstructed series show comparable trends and synchrony of high and low periods in correspondence with the gage records. In the section on surface-water hydrology, we point out noticeable differences among runoff records within selected areas of the Upper Basin. Most of these same trends are also noted in the tree-ring data series discussed in the dendrochronology section of this Bulletin. For example, the tree-ring data series and selected runoff series for the Wind River Mountains area in the Green River Basin do not exhibit a noticeable downward trend from the 1920s to the present. This represents a considerable difference from the noticeable trend in other records within the UCRB.

Three long-term reconstructions (each totalling 450 years) have been computed for the Colorado River at the 1922 Compact Point (Lee Ferry). It is reasoned that the best of these reconstructions is probably an average of two of them (Figure 10) and results in an estimated mean annual runoff of 13.5 $\pm$ 0.5 maf. The third reconstruction was calibrated by what may be biased data. In the supportive documents and hearings which came before the passage of the 1968 Colorado River Basin Project Act, the figures of 13.7 maf per year (the virgin flow from 1922 through 1967) and 13 maf per year (the virgin flow from 1930 through 1967) were used (U.S. Congress, 1968a). These figures were accepted and used by some Federal agencies at that time (Jorgensen, 1975). The judgment that these figures are valid is strongly supported by our study. All three hydrographs for the Colorado River at Lee Ferry, Arizona (the Colorado River Compact Point) show the following: (a) the period from about 1907 through 1930 was the longest period of predominately high-flow years in the entire 450 years of reconstructed record (only one other period in the early 1600s is even closely comparable); (b) the low-flow periods from 1868 through 1892 and 1564 through 1600 are of longer duration and greater magnitude than is any period during the gaged record.

Among the three subbasins drained by the Green River, the Colorado Main Stem, and the San Juan River, our reconstructions show similarities such as the abnormally high runoff period during the early 1900s and the no-analogy drought periods such as occurred in the late 1800s. All three reconstructions show a predominant downward trend from 1930 to the 1960s. These appear to be the most pronounced trends in the entire reconstructed period. There are also some noticeable dissimilarities. For example, the low-flow period during the late 1800s was most severe on the Green River and the least severe on the San Juan. Also, during the period from 1685 through 1735, a period of sustained high flow occurred on the Green and San Juan Rivers but not on the Upper Main Stem Colorado River.

Implication for Surface-Water Supply and the Water Level of Lake Powell

The annual runoff figure of 13.5 ± 0.5 maf from the UCRB takes on great significance when placed in the contexts of the "Law of the River," increasing consumptive use in the Upper Basin, and the operation of Glen Canyon Dam. From the dendrohydrological results one can place the Colorado River Compact of 1922 in the context of the reconstructed flow record. As can be seen in Figure 17, the timing of the drafting of the Compact was an unfortunate event, in that it did not occur during a representative flow period. Although the 1922 Colorado River Compact (Article III, Section a) apportioned 7.5 maf per year to both the Upper and Lower Basins, it also contains a section preventing the Upper Basin from interfering with delivery to the Lower Basin of 75 maf each decade (Article III, Section d). This is an annual average of 7.5 maf. In times of deficiency, the Upper Basin also must furnish half of the apportionment for the Mexican Treaty of 1944 of 1.5 maf per year (or 0.75 maf per year). This treaty apportionment is a national obligation, but until the Federal government provides the water it remains an obligation of the Upper and Lower Basins (U.S. Congress, 1968b). If one subtracts these two downstream obligations from the figure of 13.5 maf per year, the annual amount available for Upper Basin consumptive use is 5.25 maf. This amount is already oversubscribed in that it is covered by vested water rights which are contractually committed, water-right applications officially reserved, or unofficially projected for designated potential use (Weatherford and Jacoby, 1975).

The general picture of a collision between water demand and supply in the UCRB in the not-too-distant future is all too apparent. In fact, a study has been completed to determine the probability of future flows based upon our reconstructed record. The results, shown in Figure 18, indicate the probability of the annual flow at the 1922 Compact Point equaling or exceeding that necessary to supply the amount shown as the uppermost water requirement curve. Specific percentages are 63 in 1980; 46 in 1990; and 42 in 2000. However, if one considers the 10-year average flows, these same percentages are 73 in 1980; 39 in 1990; and 27 in 2000. Consequently, it appears that because of persistence in the flow record, long-term storage within the system is not going to significantly improve the picture. The utilization of storage facilities will serve to delay the time of actual shortage beyond that when demand meets supply, but at that point, new consumptive uses can only be undertaken by shifting water away from then-current uses or by flow augmentation. Flow augmentation is a very complex problem with many negative as well as positive aspects, but this topic is beyond the scope of this Bulletin.

In addition to mentioning uncertainty and probability with regard to streamflow in the UCRB, it should also be mentioned that there is uncertainty about the rate at which development and consumptive use will increase. Figure 19 displays a zone which encompasses likely levels of consumptive use. The most rapid development curve is from the U.S. Department of the Interior (1974), and the curve for the slower rate is from a study by Valantine (1974). Both curves show annual consumptive use exceeding annually renewable supply sometime before the year 2000.

At this point in time, Lake Powell and Glen Canyon Dam will be used to reduce

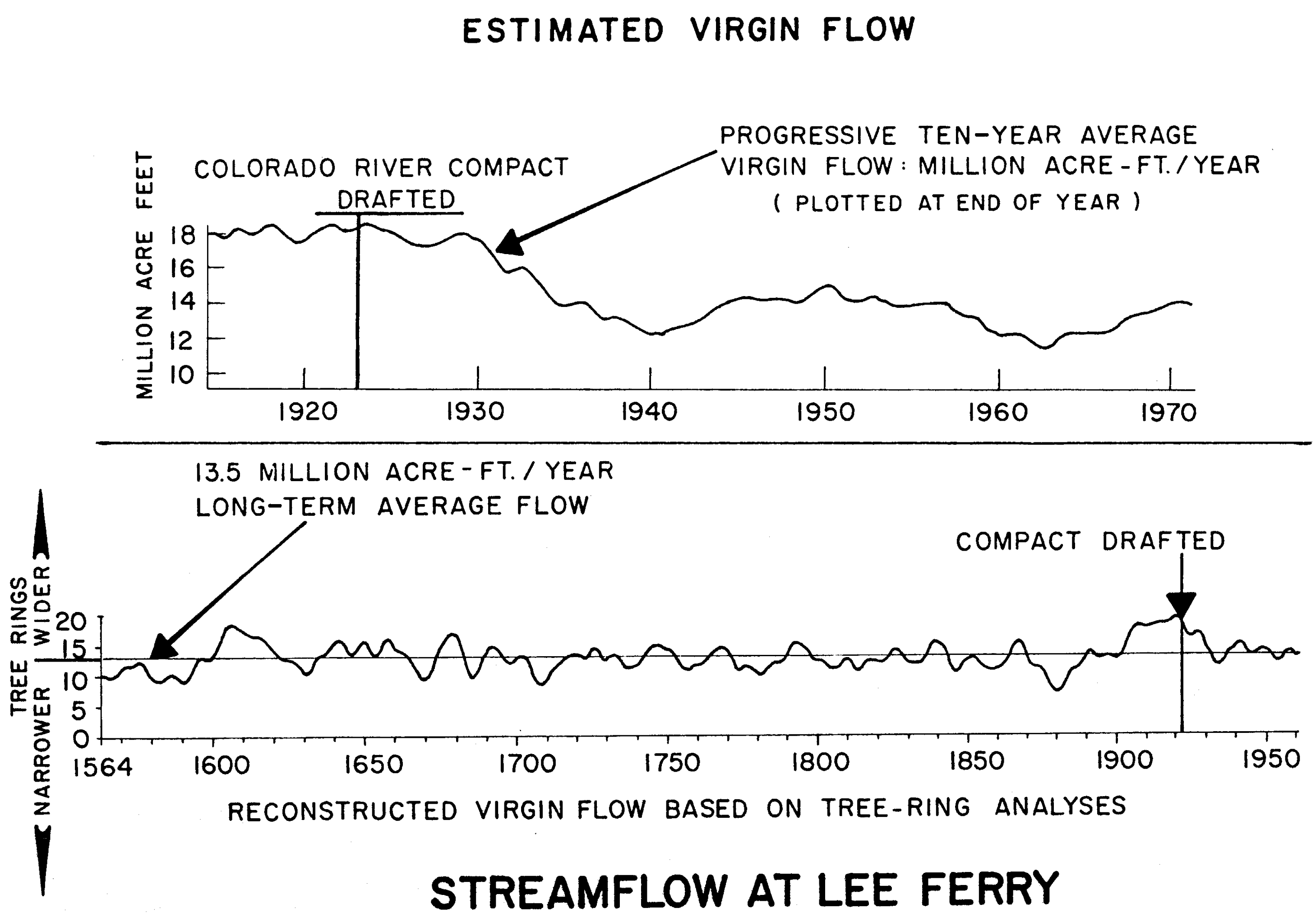

Figure 17: Flow of the Colorado River: A, Estimated Virgin Flow; B, Streamflow at Lee Ferry.

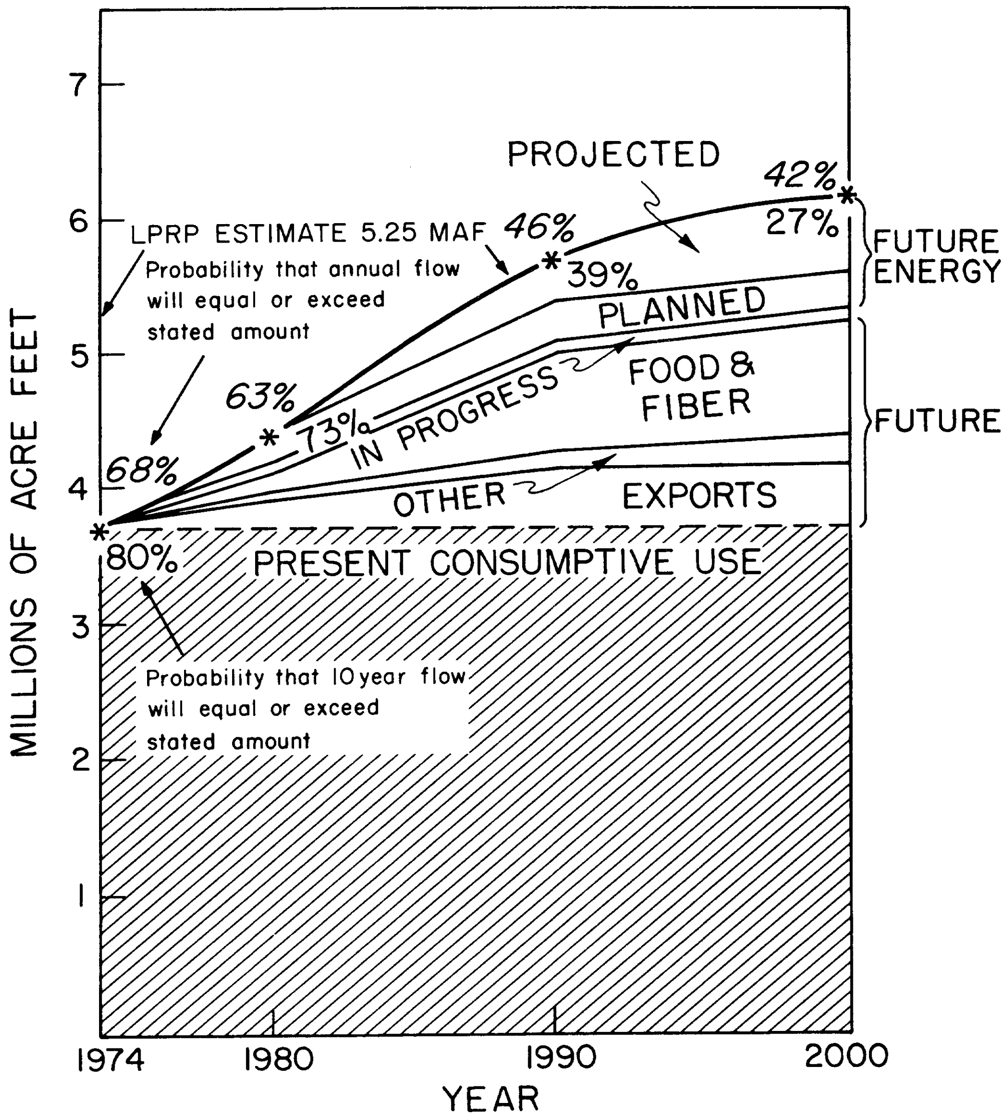

Figure 18: Surface Water Available for Consumptive Use in the Upper Colorado River Basin, and Relationship to Projected Requirement Curves for Future Energy Development (Modified from the U.S. Department of the Interior, 1974). (The 5.25-maf value is based on the estimated supply of 13.5 maf per year.)

flows to the Lower Colorado River Basin to the legal minimum and to store as much excess water as possible in wetter years. In drier years, releases from the lake will meet only the legal requirements.

Thus, the major factor in reservoir management is likely to be control of surface-water supply, and other factors such as power generation and recreation may become secondary to this control.

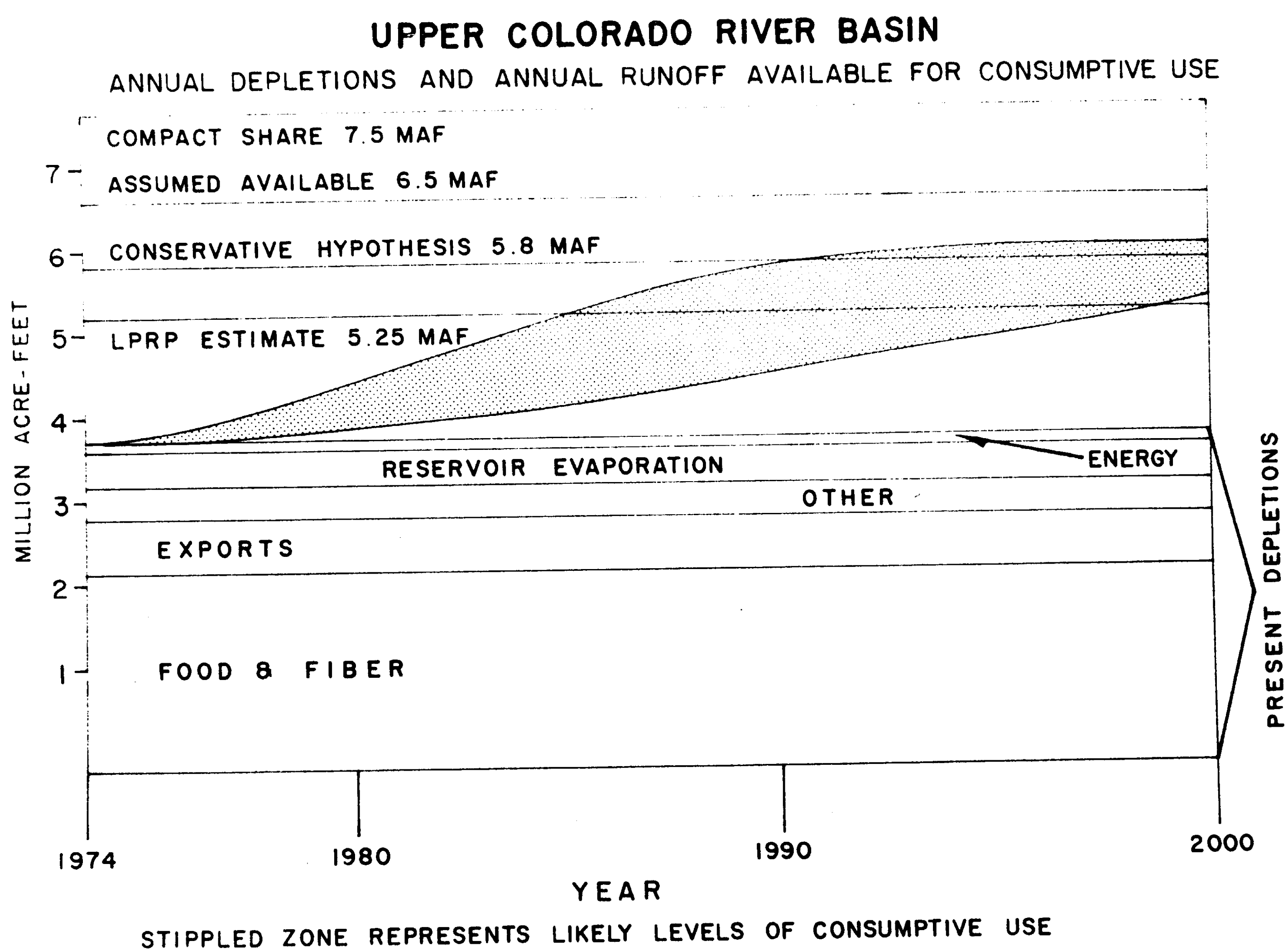

Figure 19: Annual Depletions and Annual Runoff Available for Consumptive Use, or Depletions, in the Upper Colorado River Basin. (The LPRP estimate of annaul runoff available results from this study.) (The upper curve of the consumptive-use zone is from the U.S. Department of the Interior, 1974; the lower curve is from Valentine, 1974.)

ACKNOWLEDGMENTS

Research for this Bulletin was supported by Grant No. AEN 72-03470-A03 to the Hydrology Subproject of the LPRP from the Research Applied to National Needs (RANN) Program, Division of Advanced Environmental Research and Technology of the National Science Foundation.

The authors thank the staff of the Laboratory of Tree-Ring Research of the University of Arizona at Tucson for their assistance in the research described in this Bulletin. We also thank the various staff members of the Bureau of Reclamation for their review of this manuscript; however, all results and conclusions are solely the responsibility of the authors.

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manuscript received June 6, 1975
revision received March 1, 1976

GLOSSARY

acre-foot — the amount of water needed to cover one acre to a depth of one foot: 326,000 gallons; 43,560 cubic feet; 1230 cubic meters

bank storage — in streams, lakes, and reservoirs when the water level is high, the ground-water levels nearby are raised by infiltration of water into the banks; as water levels drop, the water in this bank storage will slowly return to the original water body

baseflow — sustained runoff or streamflow composed of ground-water and subsurface runoffs

chronology — a series of observations arranged in time sequence; in tree-ring data, a series of ring-widths arranged in time sequence is termed a chronology

climatic carryover — (with respect to tree-ring analysis) the width of an individual ring is influenced by the moisture, temperature, wind, and carbon dioxide during the year of growth; these factors also influence bud formation and storage of sugars and hormones for the next year's growth; in addition, the development of root systems, and foliage and fruits for the future year's growth is also influenced by these factors; thus some of the effect of climate variables is carried over to later years' growth

coefficient of mean sensitivity (MS) — a quantitative measure of year-to-year variability in an annual ring-width series; the higher the value the greater the variability

correlogram — a plot of the auto-correlation coefficient, computed at different lags, compared to the number of lags

dendrochronology — tree-ring dating; the study of the chronology of annual growth increments of trees, and usually the determination of the actual year of growth for each increment

dendrohydrology — the use of dendrochronology to date or fix in time annual growth increments with widths or other characteristics that are strongly influenced by or related to hydrologic events; the relationships can be used to reconstruct hydrologic events occurring prior to recorded or historical events

eigenvector	given a large number of observations of a variable (e.g., tree-ring data) mapped in space, an eigenvector is a function representing a preferred mode of spatial occurrence of the variable; these functions have the properties of being orthogonal to one another, and for their respective number, of explaining a maximum amount of the total spatial variance
empirical	as used in this paper, refers to models based solely on experiment and observation and not on physical basis
evapotranspiration	movement of water into the atmosphere by evaporation from moist soil and transpiration from vegetation
F value	a computed statistic distributed according to the Fisher-Snedecor variance ratio so that it can be tested for significance against theoretical values
first-order correlation coefficient (R_1)	a quantitative measure of the tendency of adjacent values in a set of observations taken at equal intervals to be similar
historical streamflow	same as measured streamflow
homogeneity	in reference to time-series analysis, the tendency for the variability within a series to be consistent with time
hydrograph	a plot of streamflow, discharge, or runoff as a function of time
increment borer	a precision tool that can be used to bore a small-diameter hole in a living tree and extract a core that shows the annual growth increments; there is only a small-diameter (less than one-quarter inch) hole in the tree which heals in a season or two (the term Swedish increment borer is now misleading because good-quality borers are now made in other

countries, such as Finland, although the design is the same)

least-squares analysis — a statistical technique of curve fitting such that the sum of the squares of the deviations of the individual points from the fitted curve are minimum

least-squares-fit curve — a curve fit to tree-ring data to remove the biological growth curve such that the sum of the squares of the distance of the individual data points from the curve is a minimum

mean value function — a set of individual time series that have been averaged over a given time period

measured streamflow — the actual measured streamflow at a gaging station; river stage or water level is measured and then related to a stage-discharge curve for the station to give the flow rate

monsoons — seasonal wind and air mass movements caused by temperature changes between land and sea areas; seasonal rains caused by moist air brought into an area because of the monsoon wind shifts

orographic precipitation — rainfall caused by the forcing upward and hence cooling and condensation of moist air masses by mountain ranges

orthogonal — having the property of being independent (uncorrelated) in the statistical sense

periodicity — a tendency for a series of observations to possess a cyclic tendency although the wave length may be variable

runoff-producing area — most of the runoff from the Upper Colorado River Basin originates in the higher mountainous areas where the precipitation is greater and the temperatures lower than in the lower elevation semi-arid to arid areas; the former areas can be termed runoff-producing areas although there is also some runoff contribution from the lower areas

spatial — a series of observations of variables varying in space

standard deviation (SD)	a measure of the degree of variation about the mean in a set of observations
synchronous	in comparison of two time series, the tendency for the undulations to occur simultaneously and in harmony
temporal	a series of observations of variables varying in time
virgin flow	streamflow that is unmodified by human activities; for almost all major rivers the effects of human activities decrease the flow due to diversions for irrigation and other purposes; these effects can be estimated and added back to the measured flow to produce estimated virgin flow
virgin flow, reconstructed	using a proxy series, such as tree-ring-width indices, the virgin flow can be reconstructed back in time by calibrating the data with virgin flow figures
water-year	1 October through 30 September, a convention adopted by the U.S. Geological Survey for hydrology data recording and analysis

APPENDIX

RECONSTRUCTED FLOW RECORDS

The number which precedes the name of each of the flow records in the Appendix is that assigned by the U.S. Geological Survey to the gaging station.

9-3150 Green River at Green River, Utah

$\times 10^4$

DATE	0	1	2	3	4	5	6	7	8	9
1660	350	419	423	619	596	558	414	309	302	337
1670	260	341	435	502	459	527	403	312	337	519
1680	475	337	414	541	502	231	290	501	473	331
1690	392	532	609	684	455	427	508	374	468	430
1700	431	628	456	290	537	549	391	245	277	374
1710	356	338	345	419	364	461	333	237	471	595
1720	524	369	399	458	312	532	651	630	345	285
1730	380	362	378	624	552	253	210	255	418	414
1740	393	340	351	348	330	424	541	553	455	580
1750	519	324	429	612	581	324	294	391	421	378
1760	474	532	450	381	402	283	410	479	500	464
1770	464	533	359	265	341	455	477	349	324	426
1780	442	322	165	401	472	394	400	416	298	376
1790	486	568	505	381	176	256	454	477	479	400
1800	278	481	538	357	257	235	328	334	179	254
1810	466	596	533	332	367	407	476	442	406	417
1820	462	492	417	305	288	380	363	424	478	322
1830	332	413	552	398	509	387	388	566	652	633
1840	671	405	413	748	423	192	347	173	354	509
1850	398	274	417	723	564	386	401	384	478	352
1860	377	396	452	364	312	363	464	621	619	547
1870	304	239	494	380	382	369	371	424	387	243
1880	395	344	157	250	453	465	394	439	347	373
1890	480	524	367	195	249	282	203	456	439	240
1900	366	267	322	493	466	453	548	647	615	580
1910	585	639	690	784	737	627	670	880	555	445
1920	605	730	798	619	466	399	509	598	650	620
1930	588	502	626	508	390	383	388	597	528	385
1940	414	567	584	585	644	438	489	649	643	722
1950	667	602	542	451	425	400	461	543	509	372
1960	306	371	595							

9-1885 Green River near Daniel, Wyoming

$\times 10^3$

DATE	0	1	2	3	4	5	6	7	8	9
1510	434	381	300	256	294	346	394	389	337	421
1520	417	353	233	336	479	431	360	439	452	412
1530	433	457	341	258	244	302	305	388	503	487
1540	421	353	373	327	372	390	403	293	350	391
1550	432	433	476	447	398	351	363	314	265	261
1560	359	293	246	316	354	299	300	353	400	387
1570	391	434	408	421	400	420	466	482	458	458
1580	387	426	558	515	381	332	368	400	396	400
1590	427	429	435	367	289	343	427	411	340	391
1600	390	378	433	493	510	425	377	334	329	382
1610	429	433	359	329	240	325	442	420	277	262
1620	323	370	276	417	427	310	252	374	440	497
1630	394	240	219	293	360	310	353	325	271	226
1640	295	325	427	491	414	326	354	373	276	274
1650	399	470	403	378	440	470	434	362	317	377
1660	484	424	329	303	401	369	419	388	438	425
1670	376	363	439	433	427	462	451	335	356	412
1680	404	367	369	409	402	371	328	368	383	366
1690	346	336	418	416	345	305	364	368	378	391
1700	471	572	473	326	302	382	385	354	334	379
1710	402	365	344	364	447	451	371	275	383	482
1720	410	343	387	362	299	343	468	427	373	403
1730	440	374	428	460	434	408	450	427	386	396
1740	403	438	357	280	337	447	425	359	396	449
1750	468	450	381	386	378	416	417	400	322	382
1760	407	383	353	375	343	363	456	494	428	380
1770	419	433	428	359	325	382	459	436	411	461
1780	473	387	348	355	368	358	388	408	375	331
1790	377	469	542	450	418	397	407	377	384	410
1800	345	392	401	436	425	433	385	372	331	348
1810	382	428	375	321	334	414	427	347	313	411
1820	463	453	401	407	388	375	390	432	460	433
1830	379	354	396	430	373	366	372	412	420	456
1840	402	397	421	490	435	377	342	370	406	441
1850	408	352	387	484	497	406	375	402	403	352
1860	372	410	410	323	323	343	391	423	477	495
1870	432	353	339	401	449	451	420	436	417	367
1880	408	432	401	418	494	447	425	401	330	305
1890	416	427	353	344	412	407	392	406	423	451
1900	446	359	300	338	293	255	325	430	441	393
1910	327	267	302	400	433	370	406	414	399	302
1920	282	320	328	361	352	347	381	448	411	359
1930	389	406	356	314	264	256	281	343	361	365
1940	369	364	397	424	401	341	341	379	370	379
1950	425	418	390	406	380	361	398	426	398	365
1960	288	300	376	408	370	379	378	400	434	

9-2010 New Fork River near Boulder, Wyoming

$\times 10^3$

DATE	0	1	2	3	4	5	6	7	8	9
1681		260	350	326	290	255	289	313	287	256
1690	232	312	321	296	291	175	294	279	255	293
1700	331	308	310	213	257	315	258	250	237	289
1710	270	294	283	294	344	308	338	222	274	341
1720	313	199	282	313	216	221	317	332	272	198
1730	324	207	271	345	305	207	305	229	249	211
1740	279	300	289	245	237	347	330	295	302	255
1750	319	324	278	305	328	303	187	319	319	227
1760	271	351	204	282	301	193	323	303	224	289
1770	336	262	292	282	235	319	346	286	256	324
1780	395	242	240	342	254	247	319	300	279	313
1790	356	354	330	303	323	142	398	285	235	381
1800	231	223	362	245	234	239	261	270	203	230
1810	290	301	302	275	311	288	286	280	249	268
1820	358	274	259	362	236	287	338	325	355	284
1830	240	246	379	319	258	345	315	448	399	416
1840	328	348	205	408	265	220	315	224	239	329
1850	272	253	251	373	401	264	250	277	322	211
1860	220	270	290	250	197	252	346	303	341	284
1870	301	216	289	329	332	332	259	276	309	272
1880	276	313	254	307	360	359	294	287	266	231
1890	320	306	282	195	302	287	229	276	312	235
1900	266	230	259	320	303	304	317	383	349	349
1910	316	220	321	390	377	247	339	338	338	189
1920	239	277	282	260	221	324	295	338	317	263
1930	336	245	223	186	196	283	235	307	286	224
1940	173	317	263	255	346	223	305	417	335	321
1950	359	419	238	294	337	203	277	321	225	280
1960	249	249	327	236	309	268	259	258	314	

9-2995 Whiterocks River near Whiterocks, Utah

x 10^3

DATE	0	1	2	3	4	5	6	7	8	9
1750	100	70	71	127	91	54	59	89	94	90
1760	74	111	77	66	88	50	100	108	93	90
1770	103	116	76	71	77	71	98	74	55	92
1780	107	71	36	96	103	85	74	117	66	62
1790	98	113	140	113	87	49	106	123	79	100
1800	50	93	97	101	78	66	94	97	44	52
1810	102	139	122	38	62	102	142	98	85	107
1820	105	107	76	77	55	78	74	90	104	85
1830	100	100	95	82	103	74	57	90	105	120
1840	121	90	77	142	79	41	84	67	82	86
1850	90	80	71	111	131	110	71	67	101	89
1860	64	62	106	85	54	68	110	101	99	132
1870	109	45	107	83	61	82	102	106	101	50
1880	80	97	61	56	85	114	81	93	103	65
1890	99	108	101	47	69	105	67	123	135	60
1900	110	81	72	105	74	43	100	163	120	116
1910	109	119	80	100	152	109	91	130	115	69
1920	103	128	121	103	56	54	81	102	126	138
1930	111	67	123	69	43	63	64	103	94	70
1940	81	101	99	100	116	64	39	106	79	102
1950	97	79	78	74	87	64	70	96	83	53
1960	69	55	81	76	69	94	94	82	96	99

9-1805 Colorado River Near Cisco, Utah

$x\ 10^4$

DATE	0	1	2	3	4	5	6	7	8	9
1640	502	501	590	530	532	530	449	597	552	719
1650	714	648	577	383	220	752	540	585	516	558
1660	625	465	513	404	374	521	391	353	446	686
1670	360	329	570	616	609	560	648	630	732	734
1680	842	712	655	756	371	219	356	360	534	629
1690	673	790	630	701	577	567	611	678	646	634
1700	667	803	750	617	549	798	367	461	413	554
1710	575	729	677	538	352	613	548	572	584	744
1720	939	519	418	395	523	770	832	717	515	602
1730	516	416	556	615	834	477	473	530	659	626
1740	404	570	613	676	564	695	774	708	328	540
1750	497	496	518	636	687	557	390	419	635	369
1760	569	567	585	465	727	468	496	318	776	560
1770	550	669	535	292	333	557	452	362	424	519
1780	409	455	443	493	703	631	485	682	527	533
1790	816	856	820	592	575	461	702	790	319	665
1800	610	498	723	588	539	444	546	628	608	533
1810	575	760	720	463	432	611	619	656	774	589
1820	508	557	436	550	327	430	567	642	754	402
1830	479	534	689	588	486	437	595	799	744	671
1840	754	652	501	847	708	243	289	358	582	843
1850	645	256	682	759	567	304	561	428	571	724
1860	669	378	829	457	424	573	758	912	822	595
1870	529	404	670	568	544	552	582	545	581	317
1880	571	532	362	465	667	651	507	371	439	413
1890	624	517	534	491	577	624	332	619	341	549
1900	618	415	131	574	489	643	767	691	515	801
1910	803	888	716	726	927	673	864	925	727	560
1920	933	901	631	802	688	642	770	853	790	977
1930	823	475	905	496	274	610	561	641	815	626
1940	541	815	886	640	538	530	540	630	683	673
1950	551	581	836	548	403	546	528	968	757	506
1960	563	419	931							

9-0240 Fraser River near Winter Park, Colorado

x 10^2

DATE	0	1	2	3	4	5	6	7	8	9
1713				302	277	344	326	276	320	243
1720	287	279	267	248	229	232	249	341	283	292
1730	247	268	253	255	261	278	289	293	331	280
1740	273	274	225	265	242	277	280	314	262	276
1750	231	279	262	307	272	336	264	292	210	261
1760	214	286	273	308	302	296	298	258	312	285
1770	306	290	286	294	275	260	254	244	240	251
1780	237	251	270	298	290	312	259	297	261	246
1790	291	266	287	283	303	248	292	246	238	254
1800	227	231	232	248	238	249	237	250	238	260
1810	237	235	241	243	260	269	267	283	257	253
1820	238	249	265	272	234	278	255	283	289	251
1830	264	293	266	279	253	261	280	283	301	328
1840	292	292	228	296	269	251	252	228	249	244
1850	245	215	261	250	271	240	244	250	270	275
1860	290	250	263	211	286	254	301	310	278	301
1870	268	264	290	278	275	244	302	267	314	234
1880	243	275	293	299	283	273	263	251	314	343
1890	303	335	300	281	317	346	298	325	338	289
1900	310	252	244	277	286	300	309	308	301	333
1910	281	310	354	307	407	353	352	330	329	308
1920	317	353	299	428	320	282	334	270	330	261
1930	285	295	241	292	262	280	274	296	324	272
1940	278	292	308	338	287	297	250	368	301	317
1950	260	277	258	248	216	223	233	244	250	240
1960	256	246	262	237	252					

9-1100 Taylor River near Almont, Colorado

$\times 10^3$

DATE	0	1	2	3	4	5	6	7	8	9
1480	265	260	253	297	293	263	291	288	331	399
1490	443	344	295	273	166	161	292	333	134	107
1500	257	274	248	232	106	133	218	230	271	245
1510	226	237	266	218	173	237	372	427	355	332
1520	320	170	273	328	302	252	222	244	310	267
1530	222	199	259	235	269	324	257	212	356	407
1540	277	213	306	326	295	333	397	457	413	288
1550	222	331	400	403	442	484	340	218	284	304
1560	281	252	332	317	268	255	232	298	280	306
1570	280	194	167	251	253	225	303	294	240	157
1580	195	223	166	134	198	213	250	270	217	174
1590	229	205	237	286	286	294	282	231	267	246
1600	281	308	267	280	286	238	244	312	238	265
1610	204	210	231	237	293	215	225	294	212	218
1620	253	155	137	165	167	203	224	227	279	276
1630	171	179	271	240	247	241	257	235	259	227
1640	205	227	239	218	148	265	268	230	255	271
1650	259	248	176	132	308	244	258	234	276	277
1660	277	241	199	199	254	187	159	181	276	222
1670	229	246	240	210	189	226	264	302	227	224
1680	209	182	242	160	111	185	199	233	242	234
1690	246	289	292	249	271	272	276	305	236	225
1700	323	277	261	236	287	309	205	247	234	308
1710	322	255	233	214	268	263	240	264	306	328
1720	303	225	226	229	337	333	272	223	223	183
1730	272	225	246	291	315	269	255	243	310	252
1740	212	227	207	261	213	209	278	228	190	217
1750	184	223	216	245	240	246	211	277	343	307
1760	252	302	292	263	274	253	270	249	266	265
1770	303	310	227	222	233	216	211	201	207	234
1780	254	239	239	313	300	235	215	316	266	273
1790	417	374	299	269	248	169	332	276	182	324
1800	279	255	272	237	229	230	188	249	291	241
1810	235	360	319	242	253	283	311	262	248	203
1820	214	279	256	259	211	255	263	266	247	213
1830	276	348	312	249	222	211	231	291	290	245
1840	274	227	205	300	257	239	205	178	290	366
1850	249	137	279	354	314	253	220	274	296	313
1860	251	227	344	302	289	305	356	303	249	324
1870	260	240	275	244	216	243	261	270	217	163
1880	181	226	205	210	289	287	220	205	211	162
1890	178	240	203	151	229	241	164	217	200	139
1900	188	146	152	214	157	199	240	260	206	216
1910	247	322	340	300	329	302	293	252	216	272
1920	292	332	230	253	288	227	289	310	281	284
1930	282	177	252	259	188	222	244	244	225	191
1940	223	240	230	222	184	137	185	246	243	292
1950	187	214	305	219	181	257	222	275	265	208
1960	241	209								

9-1525 Gunnison River near Grand Junction, Colorado

$\times 10^4$

DATE	0	1	2	3	4	5	6	7	8	9
1641		213	220	97	138	238	221	211	259	289
1650	201	214	67	327	270	276	195	242	215	219
1660	185	153	66	163	172	191	93	256	193	219
1670	245	219	218	188	198	238	324	266	282	264
1680	178	237	169	73	161	212	251	340	329	298
1690	304	334	262	247	264	266	275	240	174	286
1700	278	270	231	301	318	235	227	200	237	301
1710	285	246	150	216	263	250	281	312	369	319
1720	156	168	160	292	315	268	192	69	165	135
1730	194	148	292	222	269	220	244	243	157	159
1740	159	257	244	267	287	258	108	174	115	123
1750	99	196	229	189	147	155	288	300	300	300
1760	216	203	208	133	231	156	217	190	226	235
1770	243	317	199	127	120	153	174	196	147	182
1780	173	202	255	307	294	254	173	288	211	211
1790	351	395	354	251	244	127	190	246	99	185
1800	226	165	211	177	154	149	132	207	212	205
1810	185	268	269	180	172	172	261	249	170	112
1820	88	190	149	216	141	175	227	214	253	162
1830	213	265	268	243	125	168	215	262	312	274
1840	246	231	168	223	214	116	130	110	229	328
1850	320	131	244	349	322	190	193	217	242	280
1860	281	170	329	266	169	238	328	313	287	306
1870	201	133	219	180	180	214	198	221	231	157
1880	163	182	138	131	201	230	193	150	160	165
1890	234	247	237	125	174	225	115	195	176	69
1900	126	143	66	170	127	200	256	312	258	256
1910	254	318	353	299	343	271	273	291	196	216
1920	260	299	198	180	219	164	207	253	237	227
1930	278	107	234	142	106	141	140	199	236	225
1940	138	226	259	209	203	140	133	156	172	225
1950	154	97	172	177	84	186	108	206	232	100
1960	184	140	214							

9-1665 Dolores River at Dolores, Colorado

$\times 10^3$

DATE	0	1	2	3	4	5	6	7	8	9
1802			299	281	331	227	226	259	207	278
1810	243	295	293	158	180	341	462	323	100	110
1820	145	362	268	143	200	290	299	251	296	232
1830	242	264	362	348	256	358	328	309	324	344
1840	380	300	206	341	351	175	313	140	354	381
1850	386	132	364	381	268	263	282	243	340	199
1860	269	57	277	298	146	304	367	392	353	367
1870	157	112	75	235	297	259	206	367	278	179
1880	213	239	227	241	274	311	260	172	422	383
1890	390	399	347	212	184	289	153	371	352	129
1900	191	323	140	310	133	361	331	370	296	373
1910	380	472	513	239	511	600	522	531	271	395
1920	594	500	451	258	352	337	501	443	463	341
1930	356	252	398	244	76	289	259	368	371	256
1940	278	513	413	290	343	293	223	376	414	525
1950	261	113	421	247	237	260	193	342	385	82
1960	348	273	226							

9-0955 Colorado River near Cameo, Colorado

$\times 10^4$

DATE	0	1	2	3	4	5	6	7	8	9
1464					394	228	228	233	231	237
1470	373	383	321	254	267	229	281	343	292	255
1480	244	283	306	227	348	242	251	253	240	270
1490	319	289	368	262	346	363	181	258	428	275
1500	224	346	294	267	305	280	267	227	289	373
1510	206	289	259	250	345	298	206	293	318	327
1520	158	305	223	324	343	222	319	191	253	302
1530	414	289	109	303	366	233	256	250	219	278
1540	274	373	169	336	380	221	303	269	233	301
1550	273	199	205	363	301	334	223	364	236	227
1560	354	321	227	282	339	359	212	277	290	246
1570	319	285	316	268	265	276	237	305	255	394
1580	237	197	330	333	218	261	331	306	260	321
1590	324	250	274	343	243	240	278	355	156	369
1600	197	313	289	228	251	197	425	249	316	287
1610	308	341	243	259	277	333	261	299	319	243
1620	290	340	222	265	342	229	274	275	304	314
1630	347	249	207	341	320	239	296	274	289	294
1640	276	251	306	272	276	322	226	290	236	285
1650	298	276	311	328	120	402	247	307	297	285
1660	336	278	267	324	225	355	281	259	262	339
1670	303	175	318	325	291	191	291	205	270	284
1680	269	275	234	359	338	237	310	285	318	264
1690	241	366	251	272	270	248	267	307	239	304
1700	250	273	253	293	214	409	251	284	277	291
1710	295	273	287	303	209	313	270	296	285	246
1720	362	251	268	281	250	254	332	334	281	315
1730	303	204	252	281	384	273	272	282	273	319
1740	201	282	277	308	254	266	290	356	215	307
1750	276	293	272	297	267	333	232	262	400	193
1760	279	281	317	210	410	250	336	153	378	284
1770	228	306	338	234	240	297	359	234	284	278
1780	225	272	271	266	301	359	215	322	346	183
1790	317	234	332	196	300	245	287	472	169	272
1800	317	222	316	343	287	250	277	302	304	269
1810	256	319	350	276	250	261	294	242	316	269
1820	250	340	258	294	212	182	320	355	395	149
1830	163	315	365	328	267	295	278	333	283	284
1840	268	290	124	339	404	186	230	312	341	368
1850	330	95	272	362	287	77	321	322	316	408
1860	347	210	359	261	208	270	285	347	257	154
1870	168	240	235	372	285	330	354	275	314	229
1880	330	322	256	248	331	276	269	246	337	256
1890	347	293	292	277	246	360	215	340	279	283
1900	284	260	117	335	360	306	316	272	187	339
1910	308	294	307	222	373	251	260	289	241	198
1920	287	351	245	322	291	190	301	283	278	295
1930	261	198	332	331	120	331	345	282	338	238
1940	222	370	314	271	262	291	278	310	235	282
1950	269	304	392	321	186	290	231	377	340	211
1960	289	176	401	233						

9-3795 San Juan River near Bluff, Utah

$x\ 10^4$

DATE	0	1	2	3	4	5	6	7	8	9
1661		251	217	218	129	257	193	164	150	129
1670	102	176	210	253	309	239	140	190	232	201
1680	280	267	271	317	107	57	250	190	199	279
1690	262	195	350	313	230	238	107	172	277	227
1700	188	360	231	198	171	278	261	148	198	206
1710	291	305	287	202	205	230	162	170	159	219
1720	400	281	216	278	137	274	353	362	197	69
1730	171	193	234	257	223	81	208	161	196	151
1740	167	150	179	259	127	246	401	367	120	363
1750	232	209	145	143	253	178	156	155	168	228
1760	194	216	227	202	222	196	304	211	267	208
1770	249	379	278	129	256	209	173	190	182	173
1780	139	172	119	215	280	200	231	323	164	145
1790	130	217	267	336	204	201	223	204	216	291
1800	215	145	270	244	264	133	135	264	184	167
1810	146	236	225	169	149	238	457	377	153	97
1820	166	332	150	115	129	222	176	164	286	188
1830	282	262	268	275	246	311	193	231	279	349
1840	395	284	185	214	240	239	195	43	218	319
1850	240	76	331	281	240	333	283	203	260	257
1860	245	73	263	183	103	175	211	300	373	423
1870	243	214	142	173	237	158	135	277	196	208
1880	175	171	182	122	205	260	236	192	297	262
1890	284	334	285	155	169	186	91	296	213	98
1900	200	145	81	234	49	216	229	286	224	247
1910	208	346	267	142	294	345	391	290	105	295
1920	401	356	269	219	262	196	304	269	247	218
1930	239	194	330	233	152	206	200	293	247	138
1940	181	330	312	207	261	216	117	173	244	288
1950	99	101	253	141	185	150	96	202	212	95
1960	227	170	203	167	117	314	232	137	218	210

9-3800 Colorado River at Lee Ferry, Arizona

50-Year Calibration Period

$x\ 10^5$

DATE	0	1	2	3	4	5	6	7	8	9
1512			120	145	160	100	92	129	157	129
1520	167	168	93	186	208	201	185	139	131	184
1530	199	114	41	99	106	146	216	147	89	165
1540	218	147	57	145	94	85	126	112	182	225
1550	184	111	156	194	154	143	203	176	91	122
1560	166	140	93	123	187	173	122	116	131	126
1570	143	151	145	102	139	120	104	173	189	138
1580	80	107	163	115	45	63	113	112	155	138
1590	89	95	68	93	121	130	182	147	123	153
1600	99	152	156	149	179	210	164	124	141	154
1610	200	157	128	130	157	186	149	178	205	142
1620	189	220	136	119	139	113	73	118	116	167
1630	137	60	47	166	129	143	121	107	128	166
1640	161	153	148	168	149	69	119	141	102	152
1650	171	201	162	89	45	159	146	162	133	134
1660	166	154	151	129	121	141	119	79	99	139
1670	78	94	131	178	155	139	119	146	160	149
1680	199	168	175	223	126	53	83	116	139	145
1690	146	159	183	180	147	147	134	160	177	147
1700	142	215	170	141	125	153	140	86	85	105
1710	143	157	166	129	105	153	124	93	135	174
1720	226	153	100	135	87	189	222	208	152	109
1730	155	136	133	176	218	102	93	106	182	133
1740	120	130	116	157	107	137	205	184	106	174
1750	142	122	119	156	164	134	88	102	141	123
1760	127	167	146	131	160	112	138	129	182	150
1770	154	187	136	85	111	135	137	120	101	134
1780	119	105	62	116	170	126	92	177	81	94
1790	172	222	191	178	122	93	203	181	102	168
1800	136	117	178	140	125	110	99	144	123	112
1810	107	195	168	90	95	129	166	158	155	136
1820	118	164	124	114	77	112	127	153	172	71
1830	100	136	168	149	122	113	109	167	189	180
1840	218	140	116	236	173	78	110	28	133	248
1850	171	46	148	206	159	103	97	93	131	147
1860	125	83	171	124	85	122	184	197	187	213
1870	130	104	150	130	111	142	149	176	139	78
1880	113	134	87	93	163	177	139	101	131	93
1890	116	158	135	78	129	163	90	181	163	104
1900	162	110	56	157	94	139	170	192	162	171
1910	154	175	177	175	209	173	190	217	143	121
1920	190	197	167	175	146	125	174	177	187	188
1930	171	94	170	136	60	106	108	165	160	133
1940	138	191	202	172	153	97	95	148	145	183
1950	113	103	205	106	87	114	88	175	158	85
1960	114	117								

9-3800 Colorado River at Lee Ferry, Arizona

65-Year Calibration Period

$\times 10^5$

DATE	0	1	2	3	4	5	6	7	8	9
1512			115	163	151	99	90	118	138	118
1520	157	183	139	202	208	175	204	142	136	180
1530	179	79	60	114	142	138	212	155	105	160
1540	200	157	66	153	104	93	125	139	171	218
1550	174	141	162	205	118	148	184	196	82	124
1560	142	131	85	151	189	171	133	123	116	139
1570	141	166	140	112	136	125	106	163	191	142
1580	66	122	167	102	56	95	121	116	143	132
1590	87	86	79	99	120	143	175	144	125	173
1600	108	158	162	153	196	222	180	118	151	167
1610	208	169	139	141	165	177	145	154	193	148
1620	184	181	131	112	123	97	118	116	104	148
1630	116	74	67	154	109	119	112	110	124	185
1640	155	149	152	158	133	81	114	134	122	165
1650	173	180	148	91	39	151	127	161	150	146
1660	159	139	156	135	114	139	116	97	97	143
1670	77	87	147	164	167	144	129	148	175	168
1680	182	174	163	210	118	58	103	119	142	151
1690	157	180	169	184	140	159	132	156	174	146
1700	148	202	171	167	131	153	112	109	103	132
1710	135	166	164	148	110	160	130	120	142	162
1720	202	149	111	140	130	198	214	198	159	132
1730	154	142	155	159	208	106	90	111	175	148
1740	124	145	126	159	121	130	193	173	111	177
1750	142	121	125	152	157	125	83	100	145	124
1760	134	165	161	110	161	116	150	123	199	148
1770	164	186	130	93	123	154	122	118	121	142
1780	121	95	95	111	178	135	102	179	94	102
1790	191	212	190	172	143	116	198	207	92	170
1800	139	118	174	144	118	126	116	155	121	127
1810	111	196	157	96	108	122	169	148	184	138
1820	116	159	137	123	85	120	143	157	169	67
1830	107	138	172	140	131	128	132	169	188	185
1840	226	155	130	223	149	69	92	69	144	240
1850	162	40	161	203	133	93	110	92	120	138
1860	131	76	167	117	107	133	196	205	194	208
1870	146	108	157	127	107	149	163	160	139	85
1880	132	127	99	119	162	165	140	102	125	109
1890	126	155	145	109	127	159	96	181	148	142
1900	154	129	75	183	119	161	186	191	155	189
1910	159	186	178	170	198	150	199	209	153	135
1920	184	207	157	185	150	141	174	200	184	199
1930	164	92	181	124	69	99	114	151	172	143
1940	143	188	200	170	147	110	92	137	152	163
1950	129	108	203	110	65	131	85	168	159	85
1960	115	115								

9-3800 Colorado River at Lee Ferry, Arizona

Framework I Study Data Used in Calibration

x 10^5

DATE	0	1	2	3	4	5	6	7	8	9
1511		113	106	146	158	95	106	139	123	104
1520	151	171	87	169	163	153	146	142	140	146
1530	151	87	36	110	105	113	171	120	83	144
1540	177	107	57	145	77	62	121	102	158	183
1550	164	148	207	217	170	145	205	186	103	154
1560	181	143	101	153	193	157	128	124	140	133
1570	149	154	126	100	128	104	104	158	176	120
1580	57	122	157	97	48	78	114	114	150	135
1590	84	90	74	81	89	123	168	103	99	142
1600	90	143	146	159	165	193	156	107	144	152
1610	198	141	109	131	146	163	141	168	167	121
1620	181	214	147	156	145	115	91	131	126	143
1630	123	48	68	159	115	128	110	92	109	133
1640	141	135	142	155	141	60	118	143	91	140
1650	159	178	151	86	84	169	129	143	115	117
1660	133	120	125	104	93	129	99	62	101	135
1670	55	76	125	145	129	131	114	105	144	129
1680	166	135	153	205	132	66	81	112	128	115
1690	141	143	145	159	114	119	134	137	152	143
1700	136	206	159	114	109	131	117	74	84	97
1710	124	137	132	118	97	153	116	85	120	155
1720	192	126	89	132	89	164	197	186	143	103
1730	152	133	133	172	184	82	104	112	173	118
1740	102	130	117	136	108	144	189	167	120	172
1750	150	130	110	154	168	117	74	116	117	107
1760	127	158	121	128	147	100	131	124	144	116
1770	137	155	105	77	95	122	128	102	91	127
1780	106	96	57	120	164	113	104	163	82	101
1790	165	178	165	158	114	74	202	139	77	168
1800	122	123	177	134	131	119	78	134	114	87
1810	119	185	142	70	75	124	137	152	162	117
1820	116	145	124	99	58	104	118	143	140	81
1830	101	123	150	128	111	95	110	159	149	151
1840	194	143	118	200	146	64	97	59	138	222
1850	139	48	163	212	136	92	112	99	135	145
1860	100	80	164	109	81	120	164	170	165	181
1870	116	92	140	109	113	141	130	152	124	80
1880	128	124	75	95	161	158	122	105	114	92
1890	126	143	121	80	131	143	76	148	158	110
1900	139	99	72	152	86	126	152	162	139	159
1910	153	165	162	169	182	166	197	220	147	127
1920	206	198	177	180	149	122	169	182	183	202
1930	154	94	188	130	54	121	113	150	163	139
1940	137	172	192	163	152	105	96	137	129	184
1950	125	108	191	102	101	138	106	189	159	94
1960	110	126								

9-3800 Colorado River at Lee Ferry, Arizona

Year-by-Year Means of Two Reconstructions

$\times 10^5$

DATE	0	1	2	3	4	5	6	7	8	9
1520	159	170	90	178	185	177	165	141	136	165
1530	175	101	38	104	106	129	194	134	86	154
1540	198	127	57	145	86	73	124	107	170	204
1550	174	129	181	205	162	144	204	181	97	138
1560	174	141	97	138	190	165	125	120	136	129
1570	146	153	136	101	134	112	104	165	183	129
1580	68	114	160	106	47	71	114	113	153	136
1590	86	93	71	87	105	126	175	125	111	148
1600	94	148	151	154	172	201	160	116	143	153
1610	199	149	119	131	151	175	145	173	186	131
1620	185	217	141	138	142	114	82	124	121	155
1630	130	54	58	163	122	136	116	99	119	149
1640	151	144	145	161	145	64	119	142	96	146
1650	165	190	156	88	64	164	138	153	124	126
1660	149	137	138	116	107	135	109	71	100	137
1670	67	85	128	161	142	135	116	126	152	139
1680	183	151	164	214	129	59	82	114	134	130
1690	144	151	164	170	131	133	134	149	165	145
1700	139	210	165	128	117	142	129	80	84	101
1710	134	147	149	124	101	153	120	89	128	165
1720	209	139	94	134	88	176	210	197	148	106
1730	154	134	133	174	201	92	99	109	178	126
1740	111	130	116	146	108	141	197	175	113	173
1750	146	126	114	155	166	126	81	109	129	115
1760	127	163	134	129	154	106	134	126	163	133
1770	146	171	121	81	103	129	133	111	96	131
1780	113	101	59	118	167	119	98	170	81	98
1790	169	200	178	168	118	84	203	160	89	168
1800	129	120	178	137	128	114	89	139	119	99
1810	113	190	155	80	85	126	151	155	159	126
1820	117	154	124	106	68	108	123	148	156	76
1830	101	129	159	139	116	104	109	163	169	165
1840	206	141	117	218	159	71	104	43	136	235
1850	155	47	156	209	148	98	104	96	133	146
1860	113	81	168	116	83	121	174	184	176	197
1870	123	98	145	119	112	141	139	164	131	79
1880	121	129	81	94	162	168	131	103	123	93
1890	121	151	128	79	130	153	83	165	160	107
1900	151	104	64	154	90	133	161	177	151	165
1910	154	170	170	172	195	170	194	219	145	124
1920	198	198	172	178	148	124	171	180	185	195
1930	163	94	179	133	57	114	111	158	161	136
1940	138	181	197	168	153	101	96	143	137	184
1950	119	106	198	104	94	126	97	182	159	89
1960	112	121								

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