Chapter 8

Application of Streamflow Reconstruction to Water Resources Management

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Abstract Streamflow reconstruction—the statistical augmentation of streamflow time series using tree-ring data—has been increasingly applied as a planning and research tool in water resources studies over the past few decades. Streamflow reconstruction in North America has evolved from a largely qualitative science in the first half of the twentieth century into a highly quantitative science that draws heavily on probabilistic theory. The historical development of streamflow reconstruction from a western United States perspective is reviewed, with an emphasis on developments of the last 30 years. Contributions to the study of water resources are discussed. Temporal extension of gauge flow records is the central contribution of the paleo record, but the statistical summary of those records and their manner of presentation are important factors in determining the value to water resources management. Probabilistic interpretations of flow reconstructions are needed because of uncertainty stemming both from limitations of the basic data and from the reconstruction process itself. Case studies are presented for the Colorado River, at the large spatial scale, and for the water-supply region of a metropolitan area—Denver, Colorado—at the smaller scale. Interaction of the tree-ring scientists with water managers and the public is a hallmark of modern applied reconstruction studies. Aspects receiving increased attention are the extent to which seasonal flows can be resolved, and how water managers and planners concerned with future conditions can overlay impacts of expected climate change on the natural hydroclimatic variability of the past as reflected in the tree-ring record.

Keywords Dendrohydrology · Tree rings · Streamflow · Water resources · Drought

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8.1 Introduction

With the narrowing gap between water supply and demand in many of the world's river basins has come an increased interest in the susceptibility of agriculture, industry, hydropower, and municipal development to climatic fluctuations. Paleoclimatic data have played a major role in convincing hydrologists and water resources planners that the snapshot of climatic variation provided by the short instrumental record may not be sufficient to capture all modes of variability important to the planning horizon. An obvious contribution of dendroclimatology is augmentation of hydrologic records—precipitation and streamflow—on which water resources planning relies. Tree-ring data are ideally suited for this purpose. Tree growth and natural runoff respond similarly to changes in net precipitation, or the residual of precipitation and evapotranspiration. Moisture-sensitive trees are widely distributed over large portions of watersheds, especially in the temperate latitudes, and frequently are most plentiful in mountainous areas, which contribute most of the runoff in semiarid watersheds.

Dendrohydrology has been defined as 'a subfield of dendroecology which utilizes dated tree rings to study and date hydrologic phenomena, such as river flow, lake level changes, and flooding history' (Kaennel and Schweingruber 1995). Because some applications of tree rings to hydrology address ecology only peripherally, it is perhaps also reasonable to regard dendrohydrology as a subfield of dendrochronology on equal footing with dendroecology. We restrict our treatment in this chapter mainly to streamflow reconstruction, a particular subfield of dendrohydrology relevant to water resources planning on the river-basin scale. Streamflow reconstruction—the statistical augmentation of streamflow time series using tree-ring data—has had a particularly rich history of application in the semiarid western United States. In keeping with the 'sharpening the focus' theme of this book, we confine the presentation to selected aspects of streamflow reconstruction we consider novel in the time frame of the last 30 years.

It is perhaps useful at the outset to distinguish streamflow reconstruction from other types of dendroclimatic reconstruction, which are thoroughly covered in other chapters. The distinction is indeed blurred, as climatic variability is a central issue in streamflow reconstruction. Droughts are commonly the focus of streamflow reconstructions and of dendroclimatic reconstructions of precipitation, drought indices, and atmospheric circulation patterns. Streamflow reconstruction is most often concerned with hydrologic drought, as manifested by unusually low streamflow over some time interval. A hydrologic drought would be mirrored by a meteorological drought, perhaps manifested in anomalous precipitation or patterns of atmospheric circulation responsible for moisture delivery. The relative severity of a particular drought by hydrologic and meteorological measures would likely differ, however, depending on many factors, including the exact drought metrics used, the watershed initial conditions, and the spatial scale of the basin.

A streamflow reconstruction study also usually includes the tailoring of analysis to some specific interest of water users, and considerable feedback from water resources planners or the agency or entity requiring the long-term information.

In this chapter we place emphasis on the interactive aspect of streamflow reconstruction with the water user or stakeholder. The statistical methodology of reconstruction is addressed only peripherally, as that has been thoroughly reviewed by Loaiciga et al. (1993). Examples of recent modeling approaches adopted can be found in recent papers (e.g., Hidalgo et al. 2000; Gedalof et al. 2004; Woodhouse et al. 2006).

This chapter begins with a brief historical background of streamflow reconstruction, followed by a section describing contributions of streamflow reconstruction to the study of water resources. Case studies on a probabilistic approach to interpretation of reconstructions (Colorado River, western United States) and on the application of reconstructions to water resource management (Denver Water Board) are then described. We close with a discussion of current challenges to streamflow reconstruction and to the adoption of reconstructions by water managers.

8.2 Historical Background of Streamflow Reconstructions

In North America, dendrohydrological studies in the 1930s began to explore the relationships between tree growth and streamflow, and the possible uses of tree-ring records for extending gauge records (Hardman and Reil 1936; Hawley 1937; Keen 1937). Hardman and Reil's (1936) work concerning the flow of the Truckee River, California–Nevada, was the first to examine these relationships in view of possible applications to water resource management, particularly in the agricultural regions of the Truckee River basin. In the 1940s, Schulman's (1945a, b, 1947, 1951, 1956) interest in dendrohydrology led him to compare variations in ring widths and annual runoff along the Pacific coast, in the Colorado River basin, the Missouri River, and for several southern California rivers. Schulman's work in the Colorado River basin was in part driven by the need to assess the long-term reliability of power generation at Hoover Dam, and the record provided by a regional tree-ring index allowed such an assessment (Schulman 1945a; Stockton and Jacoby 1976). In work for the Denver Water Board, Potts (1962) collected and analyzed tree-ring data to examine relationships with South Platte River, Colorado, annual flow and to document recurrence of droughts. The Denver Water Board was interested in estimating future storage requirements for the City of Denver's water supply and hoped to use the record of past hydroclimatic variability from tree-ring data to support these estimates. Tree-ring-based analyses to this point consisted of comparisons of ring widths and annual runoff, quantified by using correlation coefficients, and frequently smoothed to account for persistence in annual runoff and tree growth (Stockton and Jacoby 1976 and references within).

Stockton's dendrohyrolologic work in the 1970s was the first to take advantage of a suite of new quantitative methods whose routine use was made possible by the development of high-speed computers. The methods included multivariate statistical analysis for evaluating the climatic signal in tree-ring records and for reconstructing climate (Fritts et al. 1971), and standardized protocol for field sampling and tree-ring chronology development (Stokes and Smiley 1968; Fritts 1976). Stockton (1975) incorporated these techniques in his tree growth/runoff analysis and reconstructions for sub-basins of the Gila and Colorado Rivers, demonstrating the usefulness of dendrochronological methods for reconstructing records of past runoff in the southwestern United States. Building on this work, Stockton and Jacoby (1976) went on to develop a suite of annual runoff reconstructions for upper Colorado River gauges with new tree-ring chronology collections and improved estimates of natural flow for calibration. Stockton and Jacoby's 1976 report directly addressed the implication of the resulting reconstructions for water management in the Colorado River basin. Specifically, the report identified the early decades of the twentieth century, the portion of the gauge record upon which the 1922 Colorado River Compact was based, as the wettest period in the past 450 years. Stockton and Jacoby (1976) concluded that the apparent overallocation of water resources, based on this wet period, could soon lead to water demands that exceeded water supplies.

The work of Stockton and Jacoby (1976) clearly demonstrated the value of extended records of streamflow for water resource planning and management, particularly for evaluating twentieth-century hydrology in a long-term context. In the early 1980s, due largely to the efforts of Charles Stockton and W.R. Boggess, inroads were made on communication of the potential value of streamflow record augmentation by tree rings to river-basin management (Stockton and Boggess 1980a, 1980b, 1982). A number of studies followed, many focusing on the assessment of droughts and the potential applications to water resources management. These studies included reconstructions of streamflow for the Potomac River, Maryland (Cook and Jacoby 1983); the Occoquan River, Virginia (Phipps 1983); and the White River, Arkansas (Cleaveland and Stahle 1989; Cleaveland 2000). In the western United States, streamflow reconstructions of the Sacramento River, California, were made for the California Department of Water Resources (Earle and Fritts 1986), and reconstructions of the Salt and Verde Rivers, Arizona, were made for the US Army Corps of Engineers (Smith and Stockton 1981).

More recently, reconstructions have been generated for an array of rivers in western North America, ranging from the Canadian prairie region (Saskatchewan River; Case and MacDonald 2003) and the Pacific Northwest of the United States (Columbia River; Gedalof et al. 2004) to the northern and central Rockies (Yellowstone River in Montana, Graumlich et al. 2003; Boulder Creek in Colorado, Woodhouse 2001; Jain et al. 2002), the southwestern United States (Gila River in Arizona; Meko and Graybill 1995), and Gulf of California continental watersheds in Mexico (Brito-Castillo et al. 2003). Several efforts have recalculated upper Colorado River flows (Michaelsen et al. 1990; Hidalgo et al. 2000) using the same or similar data used by Stockton and Jacoby (1976) but different calibration approaches. Most recently, a number of Stockton and Jacoby's (1976) Colorado River basin reconstructions for gauges on the Green, Colorado, and San Juan Rivers, including Lees Ferry, have been updated by using a new set of tree-ring chronologies and a longer calibration period (Woodhouse et al. 2006).

Several studies have more specifically addressed management and decision-making issues with streamflow reconstructions. The first of these was a multidisciplinary study of the potential impact of severe sustained drought on the Colorado River; the worst-case scenarios were framed around tree-ring estimates of annual flow at Lees Ferry (Young 1995). Partly in response to the severe 1987–1992 drought in the Sierra Nevada Mountains of California, the California Department of Water Resources commissioned an updated tree-ring study of the Sacramento River, California, with a key objective being the estimation of long-term probabilities of low flows (Meko et al. 2001; Meko 2001). The Salt River Project (SRP), the third largest public power utility in the United States, and the largest water supplier for the Phoenix Arizona region, commissioned a tree-ring study of the synchroneity of drought in two important source runoff-producing areas—the upper Colorado River basin and the Salt-Verde River basins, Arizona (Hirschboeck et al. 2005). To facilitate use of the results by the water resources professionals and public, the final report, as well as basic data, were included in a Web site using a simple 'question and answer' format (http://fp.arizona.edu/kkh/srp.htm). An ongoing project, 'Enhancing Water Supply Reliability through Improved Predictive Capacity and Response,' sponsored by the US Bureau of Reclamation, has as one of its goals the identification of strategies for incorporating tree-ring information in river-flow modeling for the lower Colorado River basin (Jacobs et al. 2005). Public outreach and communication, in the form of meetings and a quarterly newsletter, are important elements of the project. Motivated by the 2002 drought in Colorado and in response to the needs of two major Colorado Front Range water providers, Woodhouse and Lukas (2006) tailored a network of reconstructions based on gauges in the Colorado headwaters region and the South Platte basin. These reconstructions were used as input into the providers' water system models to test the ability of the system to meet demands under a broader range of hydrologic conditions than in the gauge records alone.

Although the focus of a large number of streamflow reconstructions has been on arid and semiarid regions or areas dependent on snow-fed water supplies in western North America, there have been several recent efforts in other parts of the world. These include reconstructions for Mongolia (Pederson et al. 2001), and exploratory work on the potential for hydrologic reconstructions in the Southern Hemisphere in Argentina, Chile, and New Zealand (Boninsegna 1992; Norton and Palmer 1992). Streamflow reconstruction may be especially valuable in the Middle East, where increasing population and scarce water supplies make efficient water management essential. Application in this region is feasible, as precipitation has already been successfully reconstructed in Jordan and Turkey (Touchan et al. 1999; D'Arrigo and Cullen 2001; Touchan et al. 2003).

Many other hydrologic metrics besides streamflow have been reconstructed. In western North America alone, these include changes in lake levels, flood magnitude and occurrence, and glacier mass balance. Changes in lake level have been inferred or reconstructed for several lakes, including Lake Athabasca, Crater Lake, and the Great Salt Lake (Stockton and Fritts 1973; Meko and Stockton 1988; Peterson et al. 1999; Meko 2002, 2006). Tree growth responses to floods have been found to document both the frequency and magnitude of flood events. This work was pioneered by Sigafoos (1964) along the Potomac River in the eastern United

States, and since then numerous studies have used dendrochronological techniques to record flood events in many regions, including northern California, the southwestern United States, Colorado, South Dakota, British Columbia, and Manitoba (see review in Yanosky and Jarrett 2002). Tree-ring-based mass-balance estimates have been generated for Peyto Glacier, Alberta, Canada (Watson and Luckman 2004), and tree-ring proxies for winter glacial accumulation and summer ablation at Glacier National Park have been used to assess recent glacier retreat in a 300-year context (Pederson et al. 2004).

8.3 Contributions to the Study of Water Resources

8.3.1 *Extensions of Gauge Flow Records*

Observed streamflow records in the western United States are seldom as long as a century, and so cannot represent multicentury fluctuations due to climate variability, should such fluctuations exist. Moreover, the gauge records in a sense are a snapshot in time of one particular part of the long-term hydroclimatic history, and the snapshot may well be unrepresentative of extreme conditions (e.g., low-flow years) that may have occurred. It should also be recognized that gauged flow records are themselves imperfect measures of the volume of water passing the stream gauge, and that the accuracy of the gauged record can change over time depending on the type of gauge installed and the location of the gauge in the stream channel (Rantz 1982).

The immediate aim of streamflow reconstruction is the temporal extension of a time series of streamflow beyond the instrumented gauge record. Specifically, reconstruction targets streamflow unaffected by works of humans, which include artificial diversions, storage, modifications of the drainage network, and other factors. Streamflow defined in this way is sometimes also called 'natural flow,' 'virgin flow,' or 'runoff' (Chow 1964). The initial requirement in a streamflow reconstruction study is a time series of natural flow for statistical calibration with tree-ring records. For basins with little impact of humans, the gauged flows may provide a suitable calibration time series. For example, gauged flows for the Salt River near Roosevelt, Arizona, were judged sufficiently free of anthropogenic effects for direct use in a reconstruction model (Smith and Stockton 1981). If human influence cannot be dismissed as negligible, a modified time series of streamflow, adjusted to natural conditions by restoring reservoir evaporation losses, artificial diversions, etc., must be used in the reconstruction. Adjusted flow series were used; for example, in reconstructions for the Colorado River at Lees Ferry, Arizona (Woodhouse et al. 2006), and the Sacramento River, California (Meko et al. 2001).

The extended streamflow series provided by tree-ring analysis have contributed in many ways to a greater appreciation of the natural variability of streamflow and the susceptibility of water resources to climatic fluctuations (Table 8.1). Direct input of time series of reconstructed flows into river management models to test robustness of the system to extreme climatic variation is one natural application. An

Table 8.1 Summary of some published streamflow reconstructions in western North America (annual, water year, or summer)

River Reference	Mean flow+ (m^3/s)	Reconstruction period	Hydrologic change
South Saskatchewan, Alberta, Canada Case and MacDonald (2003)*	303	1470–1992	Relatively high mean flows in twentieth century. Droughts more severe in 1840s than in twentieth century.
Columbia, Oregon Gedalof et al. (2004)	5407	1750–1987	1840s most severe low flow of the past 250 years, but 1930s nearly as extreme. Runoff affected by land-use changes in twentieth century.
Sacramento, California Earle and Fritts (1986)*	340	1560–1979	Both highest (1854–1916) and lowest (1917–1950) flow periods occurred in the past 150 years.
Sacramento, Yuba, Feather, American (sum), California Meko et al. (2001)*	746	869–1977	Lowest average (10–50 years) means near 1300. Extreme single year low flows in late 1500s.
Yellowstone, Wyoming Graumlich et al. (2003)	88	1706–1977	Relatively high mean flows in twentieth century (except 1930s). Drought of 1930s more severe than any reconstructed drought.
Colorado River, Arizona Stockton and Jacoby (1976)*	588	1520–1961	Longest period of high-flow years 1907–1930. Drought in late 1500s longer and more severe than any in twentieth century.
Colorado River, Arizona Woodhouse et al. (2006)*	588	1490–1997	Severity of recent drought (2000–2004) likely exceeded six times in past 5 centuries, and as recently as the 1850s.
South Platte, Colorado Woodhouse and Lukas (2006)*	11	1685–1987	Record low twentieth-century flows are exceeded in severity in the late 1840s. Anomalous and persistent high flows in the early twentieth century
Middle Boulder Creek, Colorado Woodhouse (2001)	1.5	1703–1987	Low flows less persistent in twentieth century than nineteenth century. Multiyear drought in 1840s more severe than any in twentieth century.

Table 8.1 (continued)

River Reference	Mean flow^{+} (m^3/s)	Reconstruction period	Hydrologic change
Salt, Arizona Smith and Stockton (1981)*	25	1580–1979	Frequency of high flows relatively high in twentieth century. Most severe sustained periods of low flow before twentieth century.
Gila, Arizona Meko and Graybill (1995)	13	1663–1985	Clustering of high-flow years in early twentieth century. Drought in 1950s most severe on record.
White, Arkansas Cleaveland (2000)	842	1023–1985	Twentieth century has more extreme low-flow and a larger number of high-flow years than prior centuries, perhaps due to human activities.
Potomac, Maryland Cook and Jacoby (1983)	271	1730–1977	Severity of 1960s multiyear low-flow period has not been exceeded in 248 years. 1850–1873 longest period of below median flow.

*More than one river was reconstructed in this study, but only one reconstruction is featured in this table. $^{+}$Mean annual observed flows, intended to show order-of-magnitude differences in basins studied; means either taken directly from the publication listed or computed from online sources (gaged or natural flow) using all available years.

early example is the routing of Stockton and Jacoby's (1976) reconstructed flows through the Colorado River simulation model (Harding et al. 1995; Tarboton 1995). The model simulates operations specific to the Colorado River, including water allocation, reservoir operations, evaporation, hydropower generation, salinity, flood control releases, and legal and institutional constraints tied to the Law of the River (Harding et al. 1995). For a worst-case scenario in that study, the reconstructed flows for the most severe multiyear drought (1579–1600) were rearranged in decreasing order (lowest-flow year last) and input into the simulation model. Results indicated that such a drought has an estimated return period of perhaps 2000–10,000 years, and would result in Lake Powell being drawn down to dead level storage.

Two recent applications of tree-ring data in river models have utilized the time persistence properties of the tree-ring data in combination with magnitudes of flow from the observed flows. Prairie (2006), citing reconstructions of Colorado River flow illustrated in Woodhouse et al. (2006), judged that the tree-ring information on the hydrologic state (wet or dry) is very reliable, but that the magnitudes of reconstructed flows are too uncertain to justify their use in water management modeling. He applied a two-stage process to come up with realistic simulations of flow that took advantage of the perceived strengths of the observed and reconstructed data. First, the reconstructed annual flows were used in a Markov chain model to generate the hydrologic state. Second, sequences of annual flows were generated by nonparametric bootstrapping of the observed flows conditioned on the hydrologic state. The simulations of annual flow were then spatially and temporally disaggregated into monthly inputs to a basin-wide decision model. He applied this method using as input the Colorado River reconstructions of flow at Lees Ferry, Arizona, from Woodhouse et al. (2006). The example effectively demonstrated how annual streamflow reconstructions can help determine risk and reliability of various components of a water resources system.

In the second application drawing on the persistence properties of tree-ring data, Shamir et al. (2007) demonstrated how tree-ring information can be incorporated into a system of hydrologic modeling modules for water-supply risk assessment in an arid region where the water supply comes primarily from relatively shallow aquifers (micro-basins) along an ephemeral stream. The method was developed for the Santa Cruz River, just north of the US-Mexico border in Arizona. The hydrologic modules included (1) stochastic generation of hourly precipitation, (2) transformation of the precipitation into daily streamflow, and (3) surface-groundwater interaction to account for alluvial groundwater recharge. Winter wetness categories (wet, medium, and dry) were used in the precipitation module. One scenario utilized a 319-year tree-ring reconstruction of winter precipitation to establish wetness categories to guide the Monte Carlo precipitation sampling and the generation of daily flows. Results of the exercise suggested the risk of low water levels in the alluvial aquifers is greater than indicated by the relatively short instrumental precipitation and streamflow record.

The more typical direct application of streamflow reconstructions has been to place statistics of the gauged flow record in a long-term context. Most papers on streamflow reconstructions include tables summarizing the most extreme conditions in terms of single-year flows or flows averaged over several years (e.g., Cleaveland and Stahle 1989; Meko et al. 2001; Woodhouse et al. 2006). The length of selected averaging periods may include some consideration of the multiyear storage capacity of reservoirs on the river (e.g., Woodhouse et al. 2006). The mean, variance, and first-order autocorrelation of reconstructed flows generally receive much scrutiny because those statistics are widely used by hydrologists to summarize and simulate streamflow series (Salas et al. 1980). Considerable attention has therefore been given in streamflow reconstruction models to minimizing any distortion of these statistics by the biological system of tree growth and by the reconstruction modeling process.

The long-term mean annual flow is a commonly used statistic for describing the volume of water available 'on average' from a watershed. The mean is highly susceptible to sampling error, and can be severely misleading when the length of a streamflow series is short or the climatic epoch sampled by the series is especially wet or dry. Tree-ring data have, for example, consistently indicated that the long-term mean of the Colorado River at Lees Ferry, Arizona, is considerably less than suggested by the gauged flow records that start in the late nineteenth and early twentieth centuries (e.g., Stockton and Jacoby 1976; Hidalgo et al. 2000; Woodhouse et al. 2006). In applying tree-ring data to study long-term means of streamflow, it is important to recognize the limitations imposed by size-related or age-related ring width trend, which must be removed before hydrologic interpretation (Fritts 1976). Stringent quality control in the detrending of ring widths (e.g., Cook and Briffa 1990) and other tree-ring variables is required before changes in the long-term mean can be examined.

Variance, or the size of departures from the mean, is important in estimates of severity of low flows and other statistics related to water supply. Streamflow reconstructions derived by regression necessarily are compressed in variance, and so tend to underestimate the severity of dry and wet periods. Rescaling the variance such that the variances of observed and reconstructed time series are equal for the calibration period is one possible approach to circumventing the variance bias in reconstructions (e.g., Cook et al. 2004). This approach essentially treats noise (unexplained variance in regression) as signal, and so runs the risk of overemphasizing the importance of tree-ring variations unrelated to climate, but can be useful as long as it is accompanied by clear information about the reconstruction uncertainty. Noise-added reconstructions (described in a later section) are another possible approach to dealing with the unexplained variance and its effect on inferred severity of hydrologic droughts and frequency of hydrologically significant events in the reconstruction (Meko et al. 2001).

Autocorrelation is especially important in streamflow series because autocorrelation directly affects the likelihood of a negative departure following a negative departure (dry year following a dry year), and vice versa. Autocorrelation is also important to the amplitude of low-frequency fluctuations that are often of great interest in water resources planning. Comparison of autocorrelation of long-term reconstructed flows with that of the reconstructed flows for the period of the gauged record can give at least qualitative information on possible bias of the instrumental record as a long-term estimator of autocorrelation of streamflow (Meko and Graybill 1995). In reconstruction methods, much attention has been paid to minimizing the distortion of autocorrelation in streamflow reconstructions. For example, in a reconstruction of annual flows of the Sacramento River, California, Meko et al. (2001) filtered standard tree-ring indices in a preliminary step with a first-order autoregressive model, iteratively fit such that the flow series and filtered tree-ring series had approximately the same first-order autocorrelation coefficient for their overlap period.

Another approach to dealing with autocorrelation of tree-ring data was taken by Cleaveland and Stahle (1989) in their reconstruction of the White River, Arkansas. Autoregressive (AR) modeling was applied separately to tree-ring series and flow to produce AR residual time series. The AR residual flows were then regressed on the AR residual tree-ring series, the residual flows were reconstructed, and the AR flow model was applied to reintroduce persistence into the reconstruction. A third method of dealing with autocorrelation in flow reconstruction, applied to the Gila River, Arizona, was to use residual tree-ring chronologies as predictors of flow in a distributed-lag regression model (Meko and Graybill 1995). It is important to note that streamflow reconstruction models employing residual tree-ring chronologies as predictors without lags in the model are prone to underestimation of the persistence in reconstructed flows when gauged values do contain significant persistence. This point is emphasized in a sensitivity analysis in reconstruction of the Colorado River at Lees Ferry (Woodhouse et al. 2006).

Tree-ring information on streamflow has been extended in some studies to include the complete empirical distribution function of annual flow. For example, Jain et al. (2002) identified differences in the probability density function (PDF) signatures of two prominent 31-year reconstructed low-streamflow periods for middle Boulder Creek, Colorado. One period showed a general shift of the PDF to the left, reflecting generally lower mean flows. Another period showed a focused shift toward an increase in more severe low flows, but with only slightly lower average flows than the full record. The differences were presented as an example of information that could be important to water resources system management on typical planning horizons (30–50 years).

The technique of 'runs analysis' has gained popularity in recent decades as a tool for summarizing drought properties of reconstructions of streamflow and other hydroclimatic variables. In the terminology of runs analysis, a run is a series of consecutive values below some threshold; the run length is the number of consecutive years in the run; the severity, or run sum, is the sum of departures from the threshold; and the average intensity is the quotient of the run sum and run length (Dracup et al. 1980; Salas et al. 1980). Runs analysis was first applied descriptively in dendrohydrology to summarize the co-occurrence of drought in different parts of the western United States (Meko et al. 1995). A shortcoming of the method is the somewhat artificial delimitation of the temporal extent of a drought, which can be 'ended' with a single year of normal moisture conditions. The drought tally is also sensitive to the subjective choice of a drought threshold. The theory of runs analysis has recently been extended in a tree-ring context to develop a method to place any climatic episode in a temporal perspective (Biondi et al. 2005). In this method, a stochastic model is used to describe the joint distribution of run sum and run length (severity and duration).

Streamflow series have been observed to have long-term persistence, which increases the overall variability of the series and compounds the problem of prediction from a short record (Dunne and Leopold 1978). Long-term persistence cannot be effectively summarized by simple low-order autoregressive models, as described above, and requires different analysis approaches. The Hurst coefficient, or rescaled adjusted range, has long been used by hydrologists to describe long-term persistence (Hosking 1985). A tree-ring reconstruction of the Gila River, Arizona, was analyzed to place the Hurst coefficient of the gauged record in a long-term context (Meko and Graybill 1995). The empirical distribution of sample Hurst coefficients for 254 overlapping 70-year segments of the reconstruction indicated that the most recent 70-year segment provides a slightly biased (high) estimate of the long-term persistence of annual flow.

The continued development of networks of tree-ring chronologies over the past several decades has expanded the possibilities for studying multi-basin aspects of streamflow and runoff. In semiarid regions, such studies are especially relevant to water resources planning because of inter-basin transfers of water. The starting data for such studies might be existing streamflow reconstructions. For example, co-occurrence of drought episodes in the Sierra Nevada of California and the Rocky Mountains of Colorado was summarized in an analysis of reconstructions for the Sacramento River, California, and Blue River, Colorado (Meko and Woodhouse 2005). An evolutive cross-spectral analysis was used in that study to point out subperiods of enhanced coherence in runoff in the two regions. The extended records provided by the reconstructions strengthened the statistical evidence for a greater-than-chance joint occurrence of extreme low flows. Joint drought was also the subject of the previously mentioned study for the Salt River Project (SRP) (Hirschboeck et al. 2005). The focus in that study was the potential for drastically reduced runoff simultaneously in the upper Colorado River basin and Salt-Verde River system of Arizona. The motivation was SRP's dependence on imported Colorado River water from the Central Arizona Project (CAP) to buffer against reduced runoff on the Salt and Verde Rivers in times of drought. Results emphasized that severe drought years and clusters of drought years are strongly coherent across the two river systems, and suggest that drought-induced shortages in local Arizona water supply are unlikely to be offset by excessive runoff in the upper Colorado.

8.3.2 *Probabilistic Interpretation of Streamflow Reconstructions: Example for the Colorado River*

Streamflow reconstructions are statistical estimates of what the flow might have been in any given year, and the uncertainty associated with these estimates is usually displayed in the form of error bars. The user of the reconstruction can directly refer

to the error bars to judge how much importance to attach to any particular reconstructed flow, and can use the error variance of the reconstructed annual flows to derive appropriate error bars for relatively simple statistical summary statistics of annual flows, such as the *n*-year mean flow (e.g., Meko et al. 2001; Woodhouse et al. 2006).

For more complicated statistical summary statistics, mathematical derivation of the error bars may not be straightforward. An alternative approach is to dispense with interpretation of the reconstruction itself and resort to probabilistic analysis of a large number of plausible realizations of true flow derived from the annual reconstructed values and their uncertainty. Such realizations have been called 'noise-added' reconstructions (Meko et al. 2001), referring to their generation by the equation:

$$\hat{\mathbf{u}}_i = \hat{\mathbf{y}} + \mathbf{e}_i \qquad (8.1)$$

where $\hat{\mathbf{y}}$ is a vector time series of reconstructed flows and $\mathbf{e}_i$ is a sample of random noise of the same length drawn from a normal distribution with appropriate variance.

A large number (e.g., 1000) of such noise-added reconstructions constitutes a plausible ensemble of 'true' flows, which can be analyzed probabilistically for streamflow statistics. Noise-added reconstructions can be used to estimate probabilities of past occurrence of any hydrologic 'event' that can be quantitatively defined. For example, in the fourth year of a drought, we might be interested in the probability that 4 consecutive low-flow years are followed by a fifth low-flow year.

The following example utilizes the updated reconstruction Lees-B of annual streamflow for the Colorado River at Lees Ferry, Arizona (Woodhouse et al. 2006), to place the recent severe 5-year drought (2000–2004) in a long-term perspective. The reconstruction was derived by multiple linear regression from a network of standard tree-ring chronologies, extends over the period 1490–1998, and is based on a 1906–1995 calibration period. The regression model explained 84% of the variance of flows for the calibration period, verified well, and had residuals that conformed reasonably well to the regression assumptions (Woodhouse et al. 2006). The Lees Ferry observed flow for the period 1906–2004 has a mean of 18,540 million cubic meters (mcm) and standard deviation of 5368.6 mcm.

Two essential steps in the analysis of the 2000–2004 drought are the definition of the 'event' and the statement of a null hypothesis:

1. Event: flow less than a specified drought threshold for at least 5 consecutive years
2. H0: at least one event occurred in the period 1490–1988

The 'event' defined for this example is the occurrence of 5 or more consecutive years of flow below a drought threshold, which is arbitrarily specified as the 0.25 quantile of observed annual flows for 1906–2004. The 0.25 quantile adopted as the drought threshold is equal to 14,365 mcm, or roughly 77% of the mean annual flow. The event is of interest because five consecutive extremely low flows indeed did occur on the Colorado River in water years 2000–2004, resulting in steeply dropping reservoir levels and concerns among water resources professionals about the resilience of the Colorado River system to severe drought. The question rephrased in nonstatistical terms then, is how unusual was the low-flow period 2000–2004 in the context of the 509-year tree-ring record that extends over the years 1490–1998?

The severity of the recent drought is clearly evident in the time series plots of annual observed flows (Fig. 8.1, top). The period 2000–2004 is the longest run, or consecutive sequence, of years below the drought threshold. If the reconstructed flow series (Fig. 8.1, bottom) is taken at face value, it must also be concluded that the 2000–2004 drought is unprecedented in the tree-ring record, as the longest sequence of years below the threshold is 4 years. Considering the uncertainty in the tree-ring reconstruction, however, it is impossible to say categorically that there has not been another 5-year sequence of such low flows in the period 1490–1998. A more valid interpretation considers the probabilistic nature of the reconstruction. By this interpretation, the true flow in any year has some nonzero probability of being higher or lower than the reconstructed value. Depending on the reconstruction errors, which are unknown, the sequence of true flows will be somewhat different than the reconstruction itself.

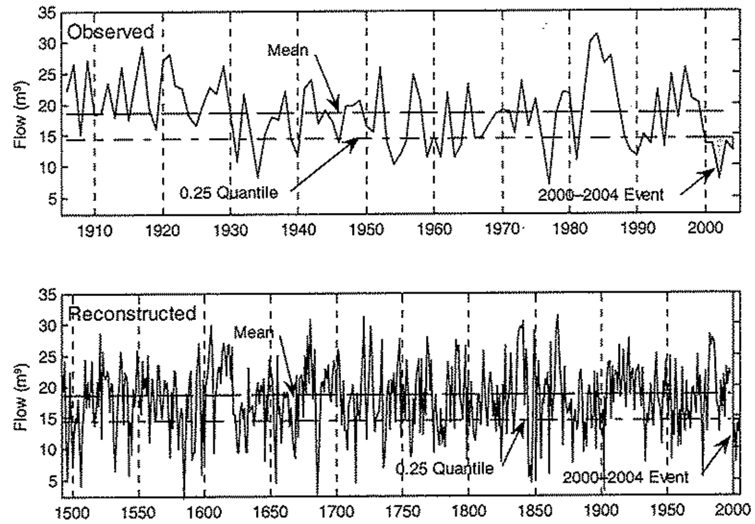

Fig. 8.1 Time series plots of observed (*top*) and reconstructed (*bottom*) annual flow of Colorado River at Lees Ferry. The mean and 0.25 quantile of the 1906–2004 observed flows are marked on both plots, along with an observed 2000–2004 'event' of 5 consecutive years below the 0.25 quantile. The maximum number of consecutive reconstructed flows below the 0.25 quantile of the observed flows is 4 years. Sources of data: observed flows are natural flow series from US Bureau of Reclamation, and reconstructed series is reconstruction Lees-B from Woodhouse et al. (2006)

To proceed with the noise-added reconstruction of Lees-B, 1000 random sequences of length 509 years were drawn from a normal distribution with mean zero and standard deviation equal to the cross-validation root-mean-square error ($\mathrm{RMSE_V}$) of the reconstruction model. Note that in using $\mathrm{RMSE_V}$ instead of the standard error of the estimate or the standard error of prediction to compute the error variances, we are imposing a larger error component than might be suggested by calibration statistics. The validation error is $\mathrm{RMSE_V} = 2337.1$ mcm, or about 44% of the standard deviation of the observed flows.

The 1000 noise sequences were each added to Lees-B to get 1000 separate noise-added reconstructions of length 509 years. Each noise-added reconstruction was then checked for occurrences of 5 or more consecutive years below the drought threshold. A count of the number of noise-added reconstructions with a drought event yields an estimated probability for rejection of the null hypothesis. For example, if just one noise-added sequence out of the 1000 generated series has a drought of at least 5 consecutive years, we can conclude the there is only a 1/1000, or 0.001, probability that the tree-ring record contains at least one event. In that case we would clearly reject H0 at the 0.01 α-level.

Results revealed that 510 of the noise-added series contained at least one drought event. The empirical probability that another sequence of 5 or more consecutive years of low flow occurred before the most recent drought is therefore $p = 0.51$, indicating that the recent 5-year drought is likely not unprecedented in the long-term record. Two examples of the noise-added reconstructions are shown in Fig. 8.2. As

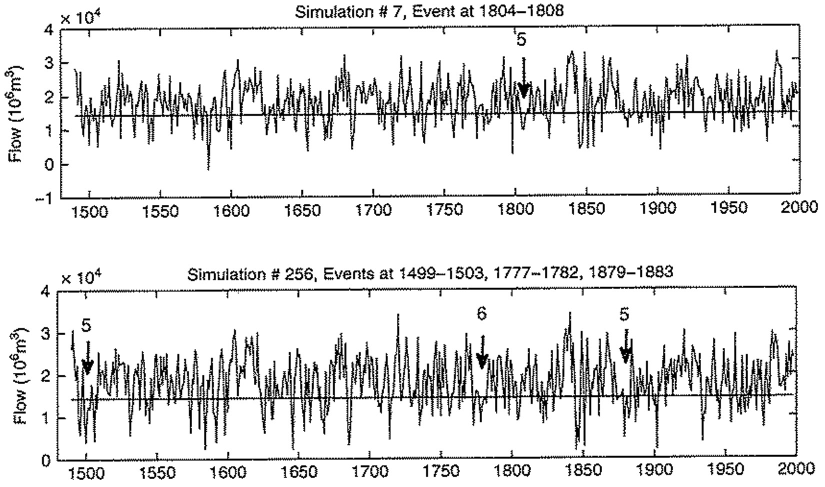

Fig. 8.2 Sample of 2 out of 1000 noise-added reconstructions illustrating occurrence of low-flow events. A low-flow event is defined as 5 or more consecutive years of flow below the 0.25 quantile drought threshold of the observed flows, 1906–2004 (*horizontal line*). The simulation at the top contains a single 5-year run below the threshold and the simulation at the bottom contains two 5-year runs and one 6-year run. A total of 510 of the 1000 simulations had such events

is indicated, some simulations may have drought events longer than 5 years, and some may have more than one event. The null hypothesis is phrased to treat all such series equally, in that each series with at least one event contributes equally to the probability. It may seem surprising that the noise-added reconstructions give such a high probability when the reconstruction itself has no events. The reason is that in years of reconstructed flow above but near the threshold, the chance is not negligible that the true flow was actually below the threshold. The noise-added series incorporate this uncertainty.

Probability estimates of hydrologic events from tree-ring reconstructions are unlikely to be used by water resources professionals without some context of comparable information from the better-understood observed flow record. The Colorado River example is extended here to illustrate how this may be done. The observed flows are limited to the period 1906–2004, but the statistics of the observed flows can be used to simulate flows as long as the tree-ring reconstruction. Differences in probabilities based on the simulated flows and the noise-added reconstruction may highlight the 'new' information provided by the tree-ring record. Conversely, similarities may attest to longer-term relevance of the short observed record.

Because the most recent years of the Colorado River observed flows have been among the lowest on record, flow statistics for designing simulation are sensitive to the truncation year for analysis. Histograms of observed flows for subperiods 1906–1999 and 1906–2004 show barely noticeable differences solely due to the low flows of the 2000–2004 drought event (Fig. 8.3). The sample mean is about 2% higher for the shorter subperiod. The histograms differ only on the left side, as expected, from the addition of the 4 low-flow years to the longer sample. Probability density functions for fitted gamma distributions to the two samples look quite similar, but differences in basic statistics are large enough to be important to the simulation results, as described below.

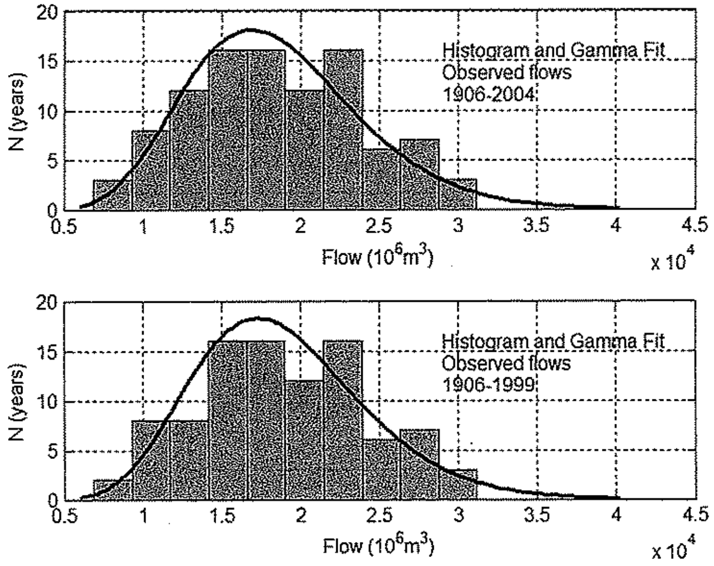

Fig. 8.3 Histograms and gamma-fit probability density functions (PDFs) of Colorado River at Lees Ferry annual flows for different analysis periods. Dropping the years of the most recent drought (2000–2004) results in a barely noticeable rightward shift in the fitted density function

For comparison with the probabilities from the noise-added reconstructions, the observed flows were simulated in two ways. First was bootstrapping, in which the observed flows were sampled, with replacement, to generate 1000 time series of length 509 years, corresponding to the length of the tree-ring reconstruction. Bootstrapping in this way destroys the time dependence in observations, which may indeed be important in creating persistent droughts like the 2000–2004 drought. The observed flows are significantly autocorrelated at a lag of 1 year ($r_1 = 0.28, p < 0.05$, $N = 99$, one-tailed). The second method used for simulation was autoregressive modeling (Salas et al. 1980). A first-order, or AR(1), model was found reasonable for this modeling. The bootstrapping and AR modeling were each repeated for the two sample periods 1906–1999 and 1906–2004 to test the sensitivity of results to including the most recent drought in the sample for designing the simulation model.

The sets of 1000 simulated flow series by bootstrapping and AR modeling were analyzed for occurrence of drought events, as described previously for the noise-added reconstructions. The empirical probability of at least one event in a 509-year series is graphed in Fig. 8.4, with results from the noise-added reconstructions included for comparison. The importance of base period for the modeling of observed flows is obvious: roughly a doubling of the probability is created by choosing the base period that includes the most recent drought. The tree-ring results are most consistent with probabilities from the drier (longer) series of observed flows, and the drought probability from the tree-ring record is higher than from simulated observed flows. The results imply that the observed flow record may be slightly biased toward underestimating the probability of drought events such as occurred in 2000–2004, and that the observed record including those drought years is more representative of long-term conditions than the observed record before 2000.

8.3.3 Applications to Water Resource Management: A Case Study Using the Denver Water Board

The Denver Water Board is the oldest and largest water provider in Colorado, serving over 1 million people across the Denver metropolitan region. Denver Water holds water rights to water supplies both in the South Platte River basin, east of the Continental Divide, and in the upper Colorado River basin, west of the Divide. A complex network of diversions, tunnels, reservoirs, and treatment plants make up the Denver Water system and is used to provide water services to their customers.

One of Denver Water's key concerns with regard to water supply is whether the instrumental gauge records (for which natural flows have been estimated back to

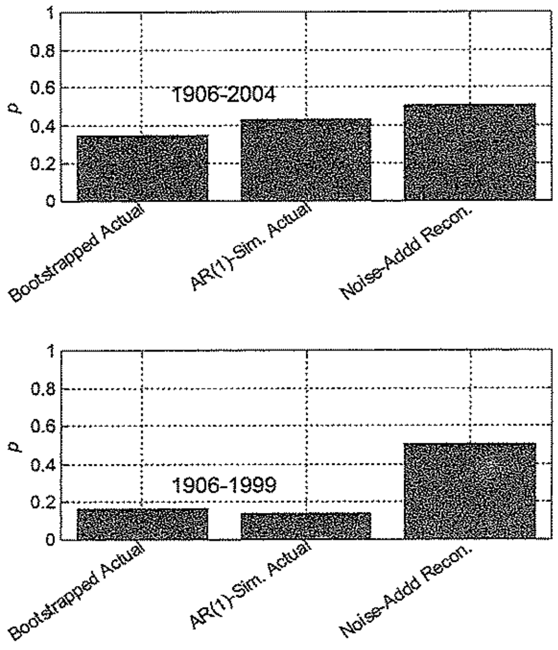

Fig. 8.4 Histograms illustrating differences in probability of drought event estimated from observed and reconstructed flows. Y-axis is probability (p) of at least one event in a 509-year period, where an event is five or more consecutive flows below the drought threshold (see text). Leftmost two bars are based on analysis of the observed flows. Rightmost bar is from noise-added reconstructions. Analysis periods for bootstrapping and autoregressive modeling of observed flows are 1906–2004 (*top*) and 1906–1999 (*bottom*)

1916) are an adequate frame of reference for future water resource planning and decision making. Denver Water planners have used the 1950s drought (1953–1956) as the 'worst-case scenario,' but the recent drought (2000–2004) called into question the appropriateness of this drought as a baseline. Are more severe droughts possible, and how would Denver Water's system perform under those conditions? Motivated by this drought, Denver Water's planning division began to consider taking another look at tree-ring-based streamflow reconstructions (after Potts' 1962 work) and their usefulness in addressing these concerns. The reconstructions would indicate if more severe droughts occurred in past centuries, and the range of their characteristics (intensity, duration, magnitude). Although the reconstructions are not used as a predictive tool, it is reasonable to assume that if extreme drought events occurred in past centuries, events of similar magnitude could occur in the future.

A meeting between a team of paleoscientists from the National Oceanic and Atmospheric Administration (NOAA) and the University of Colorado, and Denver Water planning division personnel in the summer of 2002 (the peak of the 2000–2004 drought) began a collaborative process, which evolved over the next 3 years.

In the initial meeting, paleoscientists learned of the key questions Denver Water hoped to address with tree-ring reconstructions and their concerns regarding the use of proxy streamflow data from tree rings. In turn, they endeavored to convey the science behind the reconstructions and the limitations of the proxy data. In subsequent meetings, a number of issues surfaced. These included: the availability and reliability of estimated natural flows, which would be used to calibrate models; the problem of disaggregating reconstructed annual values into the daily values needed for water system model input; and the ability of the tree-ring reconstructions to match the extreme low flows, critical for drought assessment and planning.

Some specific challenges emerged. To begin with, Denver Water wanted to know precisely how well the drought years of 2000–2002, and 2002 in particular, could be reconstructed with tree rings. The extreme low-flow year of 2002 was treated as a test case for assessing the skill of the tree-ring reconstructions. A related challenge was to evaluate the replication of other droughts in the twentieth century by the tree-ring reconstructions, and to explore techniques to better match these extremes. With regard to the uncertainty in the estimated flows, although it is known that reconstructed values more closely match the gauge values in very dry years compared to very wet years (growth is more uniformly limited in dry years; Fritts 1976), Denver Water wanted a demonstration of this in order to more closely assess the accuracy of the dry year reconstructed values. Finally, besides estimates of past water supply, Denver Water was interested in the possibility of estimating demand, using an index based on water usage, primarily in summer.

After preliminary proof-of-concept reconstructions were generated, work was begun to update western Colorado tree-ring chronologies to include the 2002 ring, and then to develop updated water year streamflow reconstructions through 2002 for Denver Water's three upper Colorado River basin gauges. Results indicated that tree growth in 2002 very well reflected 2002 low flows, and subsequent reconstructions provided estimates that closely matched the values of the 2000–2002 flows. After updating and expanding tree-ring collections for the South Platte River basin and generating streamflow reconstructions for those gauges through 2002, reconstructions resulted that were of similar high quality, especially in the replication of the 1950s and recent droughts. Along with the reconstructions, work was begun to explore approaches to refine estimates of low flow and to better describe the uncertainty related to the tree-ring-based estimates of flow. One approach was the development of an 'ensemble' reconstruction, in which reconstruction models were calibrated on numerous subsets of calibration years (Webb and Woodhouse 2003). When the ensemble members were plotted (30–40 members for the South Platte River), it was possible to see years in which all solutions converged (typically the driest years) and years in which the estimates were more variable. In several cases early in the gauge record, tree-ring estimates for a particular year all indicated dry conditions while the gauge value indicated an average or wet year. Denver Water personnel suggested errors in the estimation of the natural flows could be the cause of the mismatch in those years, something the paleoscientists had not considered. The range of scenarios presented by this ensemble approach provided a means to explore uncertainties related to statistical modeling and the sensitivity of the reconstruction to different calibration years and the quality of gauge data.

Denver Water engineers are still in the process of incorporating these results into their water system model, a major undertaking. The general approach used is to pair pre-gauge reconstructed estimates with the closest analog year in the set of 45 years (1947–1991) with known daily hydrology for the model's 450 locations to obtain the input needed for their model. In cases where reconstructed years have no analog, values for the closest year are scaled accordingly. In this way, the extended records from the streamflow reconstructions are being incorporated into the Denver Water's water system model, ultimately allowing the system to be tested by using a longer record of hydroclimatic variability than is afforded by the gauge record. A companion reconstruction of water demand, which largely reflects maximum summer temperatures and the occurrence of rainfall events at two thresholds, was also generated, allowing a comparison of long-term records of supply and demand, and the frequency of a joint concurrence of high demand and low flow to be assessed.

8.3.4 Informing the Public

Dendrohydrologic reconstructions of streamflow have played an important role in raising awareness among water managers, policy makers, and the general public that the range of variability in gauge records is just a subset of the long-term natural variability over multiple centuries. The late 1990s through early 2000s drought in the western United States caught the attention of many, and because it was the worst drought on record in many areas (depending on variable and length of time considered), it led to questions such as, 'How often do we have a drought this severe and have there been worse droughts in the past?' The public interest level was high, especially where outdoor water use was restricted, and was further heightened by media attention to the drought. Water managers had a practical interest in getting answers to these questions, while policy makers were made acutely aware that water resource and drought planning needed to consider more than the worst drought in the twentieth century.

This situation created a rare window of opportunity for dendrohydrologists to assist in addressing these questions. It also presented an excellent opportunity to inform the general public about the usefulness of tree-ring reconstructions of hydroclimatic variability. Many groups—from the Audubon Society to the local soil conservation district to continuing education law students—were interested in hearing about droughts of the past. The challenge was to present information on the tree-ring-based reconstructions regarding the current drought and droughts of the past in a way that was readily understandable by a range of audiences. New approaches to data display and visualization were considered to improve ways to convey information about hydrological reconstructions. For example, the time series of reconstructed streamflow typically shown are not readily understood by all audiences. Alternative ways to describe the long-term records of flow may be more meaningful. In particular, graphics that showed how often a year like 2002 or a sequence of dry years has occurred were of primary interest. Two examples of different ways to graphically depict streamflow reconstructions that have been well received by general public audiences are show in Figs. 8.5 and 8.6.

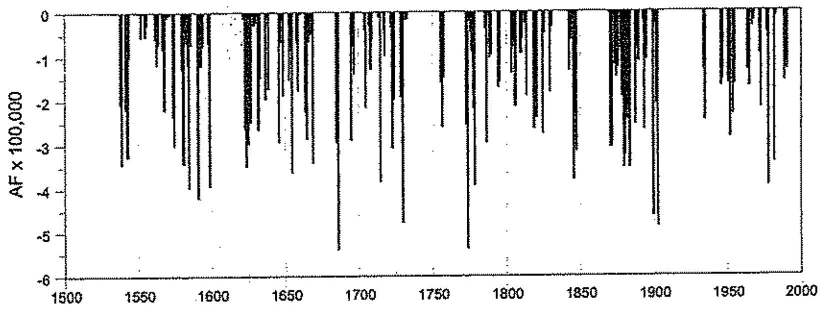

Fig. 8.5 Droughts are not evenly distributed through time. This graph shows periods of drought in the reconstructed Rio Grande River (Del Norte gauge) annual streamflow, 1536–1999. Only the years in which 2 or more consecutive years are below the mean are shown, as departures in hundred thousand acre-feet from the long-term mean

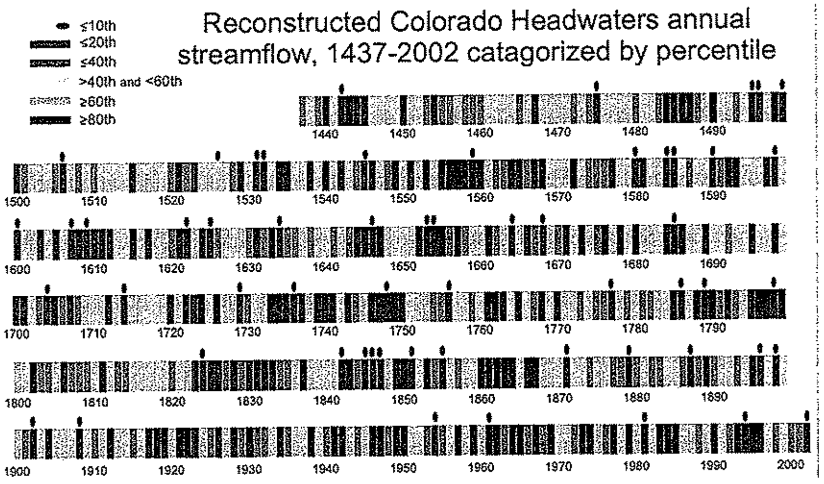

Fig. 8.6 Reconstructed Colorado headwaters streamflow (Blue, Fraser, and Williams Fork Rivers, averaged). Values are shading-coded according to percentiles of flow. The years with *dots* are the driest 10% of flows. 2002 was in this category, as were 6 years in the twentieth century. In contrast, 12 extremely dry years occurred in the nineteenth century

8.4 Challenges

8.4.1 High Flows

Attempts to reconstruct annual streamflow totals from tree-ring indices by regression methods often run up against the obstacle of heteroscedastic errors, in which the variance of the regression errors increases with the magnitude of the estimated flows (e.g., Meko and Graybill 1995; Meko et al. 2001). This is especially true the smaller the basin and the more arid the climate. To satisfy regression assumptions, one solution is log transformation of the flows before regression analysis. The reconstruction is then in log units of flow, and in such units the residuals may not be heteroscedastic. But water resources planners do not compute their water budgets in log flow units, and when reconstructions are back-transformed to original units, the heteroscedasticity returns. The problem essentially is that for basins with 'flashy' flow regimes (e.g., rapid runoff from heavy storms in arid regions), tree-ring data are unlikely to accurately distinguish magnitudes of high flows (Meko et al. 1995). The runoff events may simply occur too rapidly to leave a strong signature in soil moisture in the root zone of the trees, and in tree growth. At the same time, high flows are of great importance in water resources planning because they often contribute the pulses of runoff that refill storage reservoirs.

8.4.2 Seasonality

Cool season precipitation and snowmelt contribute proportionally more water to streamflow than warm season precipitation, especially for large watersheds. Reasons include the higher evapotranspiration losses and requirements for soil moisture recharge in the summer season, as well as the generally spotty nature of summer convective storms. Improvement of the seasonal resolution of precipitation or soil moisture signal from tree rings is therefore likely to yield more accurate streamflow reconstructions. Separate measurements of earlywood width and latewood width have proved useful in various regions for seasonal resolution of precipitation variations (e.g., Lodewick 1930; Meko and Baisan 2001; Cleaveland et al. 2003). A different issue related to seasonality concerns streamflow reconstructions in areas where the climate signal in tree growth and the main climatic contribution to annual flow do not correspond as well as they do across most of the western United States. In the Pacific Northwest, the main source of runoff is winter precipitation, while low-elevation moisture-sensitive trees are more tuned to summer precipitation (Gedalof et al. 2004). In the eastern United States, species such as bald cypress also tend to be more sensitive to summer conditions, making reconstructions of summer low flows a more appropriate hydrologic variable for reconstruction than annual flows (Cleaveland 2000).

8.4.3 Uncertainty

Uncertainty is inherent to tree-ring reconstructions of streamflow. Tree-ring data are imperfect recorders of climate, and so even a dense tree-ring network of moisture-sensitive chronologies distributed ideally over the important runoff-producing parts of a watershed will not result in an error-free reconstruction. Noise-added reconstructions, described earlier, are one possible approach to summarizing uncertainty, assuming the model is correct. The ensemble reconstructions described in the case study for Denver Water address that part of the uncertainty due to model selection given different years in the calibration set. Concisely and clearly communicating the uncertainty in reconstructions to water resources professionals is a continuing challenge to dendrohydrologists. This task is further complicated when multiple tree-ring reconstructions appear to yield widely disparate estimates for the magnitude of multiyear low-flow events and other features in the long-term record (Hidalgo et al. 2000; Woodhouse et al. 2006). Important differences in reconstructions can always be traced to differences in basic tree-ring data, hydrologic data, and modeling choices. The importance of the 'observed' flow record used for calibrating the reconstruction model is illustrated in the Colorado River reconstruction of Stockton and Jacoby (1976). These researchers reported estimated long-term mean annual flows ranging from 13.06 million acre-feet (maf) to 14.15 maf, depending on which of two existing virgin flow records were used and whether the earliest, least reliable, years of the flow record were included in the calibration. A 'best' estimate of 13.5 maf was finally adopted as a compromise based on the two versions of the reconstruction deemed most reliable. (Note: 1 maf is approximately 1.23 billion cubic meters.)

Statistical reconstruction methods, such as multiple linear regression, yield an estimate of the reconstruction uncertainty in terms of the error variance. The error variance reflects the goodness of fit of the reconstruction model, and is critical to the interpretation of the reconstructed streamflow statistics. The biases and standard errors of reconstructed streamflow drought statistics have been found to depend in degree on the goodness of fit, calibration sample length, reconstruction sample length, and autocorrelation of the reconstructed flows (Brockway and Bradley 1995). Monte Carlo studies have shown that a drought statistic derived from an observed flow record is more stable (lower standard error) than the same statistic estimated from a much longer reconstructed flow (Brockway and Bradley 1995). Reduction of the error variance of streamflow reconstructions is a major challenge in getting reconstructions to be accepted and utilized in water resources planning.

The reconstruction error variance, as useful as it is in assessing reconstruction uncertainty, summarizes only part of this uncertainty for most streamflow reconstructions. Additional uncertainty arises from the time-varying makeup of tree-ring chronologies, which can lead to reconstructed flow values based on predictors (tree-ring variables) that are essentially different from those used to calibrate the reconstruction model. An extreme example would be chronologies formed by splicing time series of indices from living trees with those of remnant wood or archaeological samples. Methods for quality-controlling and adjusting chronologies for time-varying sample size are available (Wigley et al. 1984; Osborn et al. 1997), and should be more routinely adopted in streamflow reconstruction. Another possible strategy is to tailor reconstruction models so that the equation yielding a reconstructed flow in any given year is based on a calibration model using the identical (or similar) tree-ring cores (e.g., Meko 1997).

As tree-ring chronologies are updated and additional chronologies are developed, reconstructions for the same flow record can be expected to change: the revised flow estimates will be a different linear combination of tree-ring indices from the estimates in previous reconstructions. Illustrations of such changes for reconstructions of streamflow for the Colorado River can be found in Woodhouse et al. (2006). Moreover, choices of tree-ring processing (e.g., residual or standard indices, lags or no lags, indices or principal components) can lead to different reconstructions from the same basic tree-ring measurements. Because the 'true' model relating flow to tree-ring indices is an abstraction and is unknown, it is important that more research address the sensitivity of reconstructed streamflow features to modeling choices.

Uncertainty in the low-frequency component of streamflow variability is another aspect of streamflow reconstruction that cannot be satisfactorily addressed with calibration and validation statistics of reconstruction models. First, the flow record for the period used to calibrate and validate the model simply may not be representative of the low-frequency behavior of the long-term record. In that case, we do not know how well the tree rings might track the low-frequency flow variations, and we must assume that low-frequency features—such as broad swings above and below the mean in tree growth—reflect similar variations in flow. Second, the detrending operation in conventional standardization places a lower limit on the frequency of climatic variation resolvable with the tree-ring index. That limit depends on the length of the tree-ring series and choices of detrending curve by the researcher developing the chronology (Cook et al. 1990, 1995). Regional curve standardization (RCS), which depends on identification of a generally applicable function of expected ring width with tree age, has been applied in dendrohydrology in an attempt to circumvent the frequency-response limitation (e.g., St. George and Nielsen 2002). Unfortunately, RCS requires intensive sampling, with trees of various ages represented throughout the period of record (Briffa et al. 1996). Few river basins may afford such a luxury of moisture-sensitive trees.

Uncertainty can never be completely eliminated from streamflow reconstructions. A streamflow reconstruction relies on a statistical relationship between streamflow (observed or adjusted to natural flows) and tree-ring chronologies distributed over the basin. Increased tree-ring site coverage and improved statistical methodology may increase the strength of the relationship. Uncertainty may eventually be reduced by incorporating information from tree-ring variables other than ring width index in the reconstruction model. Variables might include wood density (e.g., Briffa et al. 1988), stable isotope ratios in tree rings (e.g., Leavitt and Wright 2002) and the anatomical features of cambial cells (e.g., Vaganov 1990; Vaganov et al. 2006). Such efforts can never arrive at a perfect reconstruction, but improvements in accuracy may enhance the usefulness of the reconstruction for water resource management.

Possible changes in basin characteristics over the period covered by the tree-ring record impose on streamflow reconstructions a layer of uncertainty not amenable to assessment with statistics on calibration accuracy or validation accuracy. Reconstruction models assume that the statistical relationships derived for the calibration period are stable over the long term, and this assumption may be violated if basin conditions have changed. For example, if the vegetative cover of the basin was drastically reduced (e.g., by fire) during some intervals, the runoff from the basin at those times would be greater than expected from a statistical model calibrated under modern conditions. On the other hand, an error of this kind may be unimportant to water managers who are interested in the possible effects of climate variability on runoff given existing vegetation coverage.

8.4.4 Communication

The extended records of hydroclimatic variability provide valuable information about the range of natural variability beyond that provided by gauge records alone. This information has important implications for water resource planning and policy making. The challenge is to move from these implications to determine the ways these data can actually be applied to water resource management. Collaborative work between water management agencies and paleoscientists, as described in the example above with Denver Water, has demonstrated the potential usefulness of these data in planning and management. In the spring of 2002, a workshop was held in Tucson, Arizona (Garrick and Jacobs 2005), that brought together paleoscientists and water management agency personnel with interests in the Colorado River basin. Group discussions during the workshop brought to the forefront some of the challenges in applying paleodata to water resource planning and management. First and foremost was the need for better communication between paleoscientists and water management personnel to improve scientists' understanding of management decision-making concerns, as well as water managers' understanding of the science behind the data. Part of that challenge is finding water managers willing to look beyond traditional management tools, and dendrohydrologists willing to think about alternative approaches to standard dendrohydrological methods. Forming successful partnerships is a time-consuming process for all parties involved. However, due to the impact of recent droughts, coupled with increased demands on water supplies and the potential for anthropogenic climate change, the water resource community has begun to recognize the value of these extended records. Our challenge is to improve communications with water management personnel so that we can find better ways to provide the data and information needed for planning and decision making.

8.4.5 Climate Change

The regional impacts of climate change on water resources are becoming evident in the declining snowpack in the mountains of the western United States, and particularly in the Pacific Northwest (Mote et al. 2005). The decline is mostly attributed to warming winter temperatures, even with periodic and regional increases in precipitation (Mote et al. 2005). Effects of this reduction of snowpack on hydrology include earlier runoff dates and changes in the distribution of runoff over the course of the water year, with more runoff earlier in the water year (Stewart et al. 2004). These changes could result in greater losses due to evaporation and an overall reduction in water year flows, if not compensated for elsewhere in the hydrologic cycle. Future climate projections suggest large-scale warming on the order of 1–2°C across the western United States over the next half century (Barnett et al. 2004).

These trends and projections bring up the question, is the record of past hydroclimatic variability an appropriate analog to future conditions? In some respects, the climate of the future will be unlike the climate of the past; however, natural hydroclimatic variability is likely to continue, superimposed on changes in climate due to anthropogenic activities. An understanding of natural hydroclimatic variability on decadal and longer timescales can be obtained only from centuries-long reconstructed records, and is critical for understanding the large-scale, slowly varying oceanic/atmospheric drivers of climate. These large-scale controls are likely to continue to operate in the future, and a baseline knowledge of the role of oceanic/atmospheric conditions in long-term regional hydroclimatic variability is necessary to understand how the climate system operates now and how it will under warmer conditions. The challenge will be to blend the knowledge gleaned from the past with projections for climate under climate change scenarios to get a better indication of the range of hydroclimatic conditions and events to expect in the future.

8.5 Conclusion

A.E. Douglass, in the foreword to Edmund Schulman's (1945a) landmark report on tree-ring hydrology of the Colorado River basin, wrote that he believes Schulman 'offers something of novel importance and value to the hydrologists of the West,' and that the report will 'carry over to the managers of hydroelectric and reclamation projects about the world a good idea of the type of information that may be secured from properly selected and analysed [sic] trees.' Some 50 years later, we see that much has been accomplished but that the potential of tree-ring analysis in hydrology has only begun to be tapped. Early studies were most intensive in the western United States, with groundwork for quantitative streamflow reconstructions laid by H.C. Fritts and C.W. Stockton. The geographic scope has expanded with the growth of dendrochronology as a science, the development of tree-ring laboratories in various countries, and the spatial extension of tree-ring networks. The contributions of dendrohydrology continue at an accelerating pace as human demands on limited water resources increase and the need for efficient long-term planning in water

management becomes more urgent worldwide. In the western United States, severe and widespread drought conditions in recent years have only served to increase the demand for streamflow reconstructions by water management personnel who have recognized the value of the extended records.

New methods are constantly under development to better synthesize the information from streamflow reconstructions for use by water resources professionals. An overriding goal is the adoption of quantitative reconstructions in water resources planning and operations. To this end, perhaps as important as the scientific advances is a proactive approach to communication that includes much direct interaction of tree-ring researchers with water resources professionals and the public to emphasize the potential value of augmented time series of streamflow.

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