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Using the Past to Plan for the Future—The Value of Paleoclimate Reconstructions for Water Resource Planning

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ABSTRACT Drought, growing demand on limited water supplies, and the impacts of climate change are all challenging the management of water resources in the western United States. While there is an increasing focus on climate change, information from the past in the form of tree-ring reconstructions of hydrology can provide information critical to water resource management. These reconstructions document the hydrologic variability that has transpired over past centuries, including events more extreme than those experienced in the modern period. Long-term natural variability, including droughts, will underlie the effects of anthropogenic climate change in the future. Reconstructions of past flows have been generated by researchers since the 1970s but have only recently been incorporated into resource planning and management. A number of challenges exist

for the incorporation of this information into management, but a variety of motivations have prompted collaboration between researchers and water resource practitioners to develop ways this information can be applied. Examples from Denver Water, the Salt River Project, and the Bureau of Reclamation illustrate both the challenges and innovative uses of the reconstructions to address management questions. Looking into the future, tree-ring records supply important information about past climate, which, when combined with projections for future climate change, can provide a basis for robust water resource planning.

9.1 The Role of the Past in Planning for the Future

Since 2000, widespread drought conditions in the western United States have coincided with the emergence of climate change on the agenda for water resource management and planning in the region. While the causal linkage of the drought conditions with climate change is still debated (e.g., Cayan et al. 2010; Trenberth et al. 2013), it is clear that hydrologic conditions in the West are increasingly perceived through the lens of climate change. And as the impacts of climate change have become more widely anticipated, if not experienced, the past as a paradigm for future climate and hydrology has been called into question. The recent proclamation that "stationarity is dead" grabbed the attention of water managers (Milly et al. 2008, p. 573), and indeed, human activities (greenhouse gas emissions, land use, and land cover changes) are now a major influence on climate, and thus on the hydrologic cycle, unlike in the past.

Paleoclimatology, however, has long demonstrated the inherent nonstationary nature of the hydroclimate, clearly showing that the statistical characteristics of hydrology over the twentieth century do not represent the full range of variability that has occurred over longer timescales. Proxies of climate extending centuries into the past have provided evidence of climate variations on timescales of decades to centuries that have not been detectable in the shorter modern records (e.g., Gray et al. 2003). These records, by virtue of their length, almost invariably show extremes in droughts (and floods) more severe than those documented in instrumental records, reinforcing the need to look beyond the gage record to understand the range of conditions that occur under natural climate variability alone. This range of variability will continue in the future, underlying anthropogenic climate change (Meko and Woodhouse 2011). While projections of future climate from global climate models (GCMs) are critically important for anticipating the impacts of humans on future hydrology, even the most recent models appear unable to capture the range of decadal to multidecadal variability documented in paleoclimatic records (Ault et al. 2014). Because recent and ongoing droughts are likely due to both natural variability and the effects of climate change (e.g., Wang et al. 2014), understanding the extents of drought severity and duration that the natural system can generate is as important as understanding how humans may be exacerbating drought conditions through anthropogenic climate change.

In addition to the longer-term challenges of climate change, many water resource systems in the western United States are currently at, or approaching, capacity. For example, decadally averaged demands have recently exceeded supply in the Colorado River Basin (USBR 2012). Consequently, the recurrence of previously experienced variability in supply (i.e., droughts) over the next few decades could have major impacts on water management, even before projected anthropogenic changes are felt significantly. The range of streamflow variability possible in this time frame is arguably better captured by tree-ring data than either observed records or climate projections. One of the earliest studies that elucidated the nature of decadal-scale hydrologic variability and its implications for water resource management was the first tree-ring reconstruction of Colorado River annual streamflow (Stockton and Jacoby 1976). This reconstruction extended the gage record back to the mid-sixteenth century and clearly showed that the Colorado River Compact negotiations were based on an anomalously high period of flow, but also that low flows much more severe than those of the gaged record had occurred in the past. Updated reconstructions of the Colorado River identified the 1100s as the period with the lowest 25-year average flow in 12 centuries (Meko et al. 2007). Statistical analysis further indicated that such a drought might be expected about once every five centuries from the natural variability of the observed flow itself, and application of a long-term planning model showed that the recurrence of such a persistent period of low flow could reduce Lake Mead levels to "dead pool" (i.e., no usable storage) in two decades, given current allocations (Meko et al. 2012).

Tree-ring data provide a way to bridge traditional resource management with planning that considers long-term future climate and a plausible range of hydrologic variability. There are a number of ways the tree-ring information is being used by water resource managers (Woodhouse and Lukas 2006a; Rice et al. 2009). In many cases, water providers and agencies seek a context for assessing recent or current drought events. Sometimes, a qualitative assessment is most applicable, and a visual comparison of the gaged record with a centuries-long reconstruction of past flow provides the awareness needed to understand the limitations of the gage record (Woodhouse and Lukas 2006a). In other cases, a probabilistic assessment of critical features of the gaged record is most useful, such as for the severe drought years in the Colorado River Basin, 2000–2004. Tree-ring records classify that drought as a severe event in the long-term context but also indicate that at least one other drought of similar magnitude likely occurred over the past 500 years (Woodhouse et al. 2006; Meko and Woodhouse 2011). Tree-ring reconstructions have also been used to generate streamflow scenarios to test current management practices under highly stressful but plausible conditions, providing awareness of possible challenges in the future and an impetus for change. In an example of this, the Salt River Project (SRP), the Phoenix metropolitan area's largest water provider, assessed the impact of severe droughts over past centuries on reservoir depletions in the context of newly created operating guidelines (Meko and Hirscboeck 2008; Phillips et al. 2009). Another type of application examines reconstructions of past streamflow in the context of projected anthropogenic climate changes, anticipating a future with hydrology and water system outcomes well beyond the bounds of twentieth-century variability. In California, new and updated reconstructions of Sacramento River and San Joaquin River flows are being used to evaluate possible future hydrologic droughts as generated by models incorporating effects of changes in greenhouse gases, relative to droughts occurring under natural variability over the past thousand years (CADWR 2014).

9.2 Tree Rings as Records of Past Hydrologic Variability

Tree-ring reconstructions of past hydrology are based on the fundamental principles of *dendrochronology*, the science and dating of annual growth rings in trees (Fritts 1976).

These principles dictate, first, that trees growing in sites that are climatically stressful will record variations in the climate factor most limiting to growth. In much of the arid and semiarid western United States, the factor most limiting to growth is moisture; thus, wide rings reflect wet years, and narrow rings reflect dry years. Sampling trees at lower elevations and at sites with thin, well-drained soils, south-facing aspects, and little competition from other trees helps enhance the moisture signal in the ring widths (Fritts 1976). While the relationship between tree growth and precipitation is obvious, the link between tree growth and hydrology is less direct. The same climate factors, precipitation and evapotranspiration, mediated by the soil, are integrated in a similar manner into both annual streamflow and annual ring widths of trees (Meko et al. 1995; St. George et al. 2010). In the semiarid West, it is primarily the cool-season precipitation that links tree growth and hydrology; in their annual increments (i.e., ring width and water year flow), both reflect the cumulative precipitation that builds the snowpack and/or replenishes soil moisture during the period of low evaporative demand.

Trees from climatically stressed sites and species known for longevity and clearly discernable annual rings are targeted for collection. Living trees are sampled with increment borers, while cross sections from dead trees may be cut with a chainsaw. The samples from dead trees are intended to extend the tree-ring record and can often add centuries to the record available from living trees (e.g., Meko et al. 2007). Replication, another principle of dendrochronology (Fritts 1976), serves to enhance the climate information common to all trees, while minimizing the tree-to-tree variability in the ring widths. In arid and semiarid locations, about 20 trees (and two cores per tree) are typically sampled at each collection site.

In the laboratory, cores and cross sections are prepared for analysis by sanding each sample until the cells that make up each ring are clearly visible under a microscope. Rings in each sample are dated using a method called *cross dating*, in which the patterns of wide and narrow rings are matched between trees (Stokes and Smiley 1968). This process is undertaken instead of merely counting rings to ensure each and every ring is correctly dated to the exact calendar year. This process also allows the dating and incorporation of nonliving tree samples. Dated rings are measured to the nearest 0.001 mm using a sliding-stage micrometer. The ring-width series for each sample is then detrended to remove the effects of tree geometry (wider rings in the center of the tree typically grade to narrower rings on the outside) and age-related features unrelated to climate. Detrended sequences of ring width for each sample are averaged together to create a site chronology. The site chronology is the fundamental unit used for reconstructing past climate and hydrology.

A reconstruction of streamflow is an estimate of past conditions based on a statistical model of the relationship between a selected set of tree-ring chronologies and gaged flows (Figure 9.1). A reconstruction model is typically calibrated using tree-ring chronologies (or aggregates of chronologies) as predictors and a gage record as the predictand. Some version of multiple linear regression has been the most common approach for model calibration, but a number of other statistical approaches have been explored in recent years (e.g., Saito et al. 2008; Gangopadhyay et al. 2009). Reconstruction model calibration requires observed records that reflect natural flow conditions, either by virtue of the hydrology being relatively unaffected by diversions or depletions or through explicit estimation of natural flows. Tree-ring chronologies selected as candidate predictors should be significantly correlated with the gage record of interest. The period of time common to both gage record and tree-ring data is ideally 30 years or more.

The accuracy of a streamflow reconstruction model is usually measured by the proportion of variance of the gage record explained by the model and by the size of the departures (errors) between the estimated and observed flows. Differences in the statistical properties

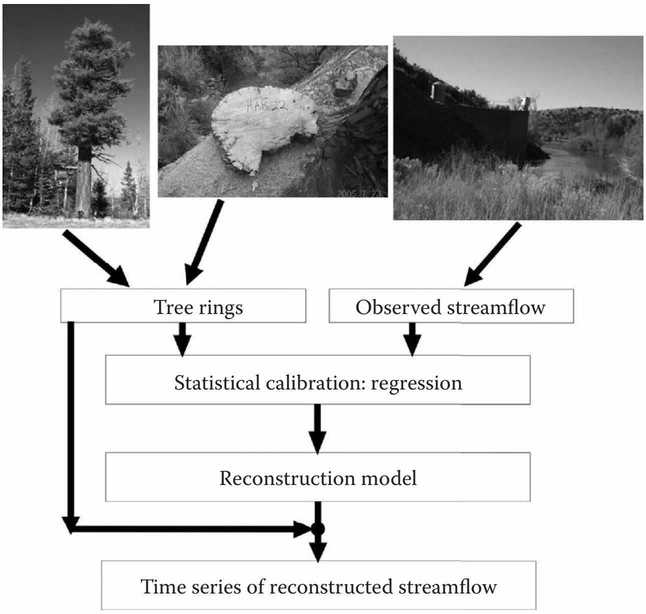

FIGURE 9.1
Flowchart showing reconstruction steps.

(e.g., mean, variance, range, autocorrelation) of the observed and reconstructed records are also compared.

The model is validated with data not used in fitting the model and estimating the regression coefficients. A visual comparison is very useful in showing how well the reconstruction replicates particular years of interest (Figure 9.2). Once the reconstruction model is tested and evaluated, the tree-ring data for the full period are applied to the model to generate the full-length reconstruction. If the time coverage of individual chronologies varies greatly, the entire procedure of calibration and validation may be repeated for different

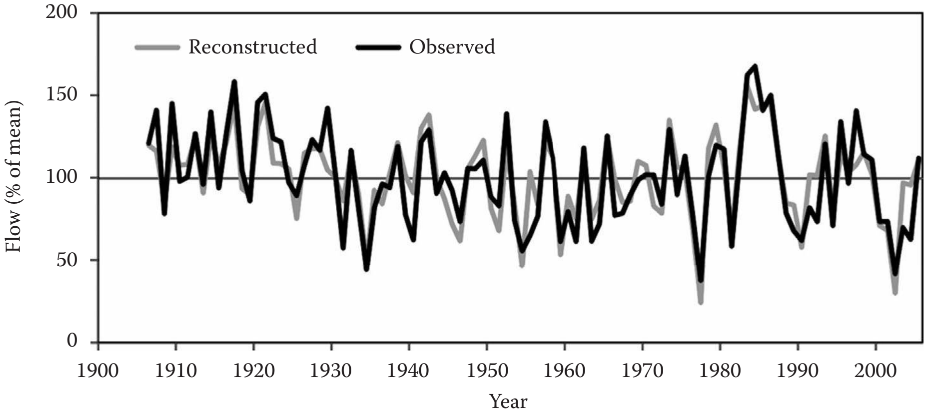

FIGURE 9.2
Time plots illustrating agreement of observed and reconstructed annual flows of Colorado River at Lees Ferry, Arizona. Example shown is for the time-nested regression model used to generate 1365–2002 CE segment of Meko et al. (2007) reconstruction. Flow is plotted as percentage of the 1906–2005 observed mean flow.

subsets of chronologies, with a final reconstruction spliced together from the segments provided by the subset models (e.g., Meko et al. 2007).

One important aspect of the reconstruction that is not always well communicated to water managers is the uncertainty in the reconstruction. Even the most skillful tree-ring reconstructions do not explain more than 70–80% of the variance in a gage record. Most often, the unexplained variance is in the failure of the reconstruction to replicate the most extreme values, and in particular, the most extreme high flows (Figure 9.2). In developing a reconstruction, there are a number of choices made, including the tree-ring data selected for the reconstruction, the specifics of the reconstruction approach, and the years used in the calibration. There is no set of choices that lead to the "correct" reconstruction; each solution will be slightly different. Because of this, a reconstruction should be considered a plausible estimate of flows using a given set of data and modeling decisions. The earliest years of flow reconstructions may also be somewhat less accurate than implied by model statistics because of lower replication (fewer trees) in the earlier parts of tree-ring chronologies (Meko et al. 2012).

9.3 Why Reconstructions Have Gained Acceptance by Water Managers in Recent Years

While streamflow reconstructions from tree rings have been available since the 1970s and 1980s (e.g., Colorado River flow, Stockton and Jacoby 1976; Sacramento River flow, Earle and Fritts 1986), the water resource management community in the western United States has not incorporated this information into their planning and management activities until recently. A convergence of multiple factors over the last 10–15 years likely motivated this, including severe and prolonged drought, water demands outpacing supplies, the growing reality of climate change, a set of outside-the-box-thinking resource professionals, and a shift in the way that researchers view the utility of their science and their interactions with stakeholders.

One of the first motivations for using tree-ring data was to assess the 2000s drought, which strongly affected water resources in the Colorado River Basin and elsewhere. The iconic droughts of the twentieth century, the 1930s Dust Bowl, the 1950s, and the late 1980s to early 1990s, were matched or exceeded in severity by early twenty-first-century drought conditions in many locations. This raised the following question: Have there been worse droughts in the more distant past? The extended records from tree rings almost invariably show that the period of instrumental record does not contain the full range of natural variability that has occurred over past centuries. In some cases, worse conditions may have occurred within the past few centuries (e.g., Rice et al. 2009); in other cases, the twentieth-century drought extremes have not been exceeded since the 1100s (e.g., Meko et al. 2014). Although droughts may be measured in a variety of ways, these assessments indicate that at least by some measures, the droughts that have occurred since 2000 are not unprecedented, in the context of the past 1000–1200 years.

Another motivation for the use of extended records of flow from tree rings is the increase in society's vulnerability to drought conditions in recent decades. The publication of the first reconstruction of Colorado River streamflow (Stockton and Jacoby 1976) coincided with the start of the driest water year (1977) in the twentieth century, but the two decades that followed saw mostly above-average streamflows in the Colorado River Basin. This was also a period of rapid growth and development in the urban areas—Los Angeles, Las Vegas, Phoenix, Tucson, Salt Lake City, Denver—that at least partly depend on Colorado River water supplies. When persistent drought conditions commenced in 2000, the impacts were strongly felt, but by some measures, conditions were no worse than the 1950s drought (e.g., Weiss et al. 2009). The vulnerability to drought had increased due to greater demands on limited water resources, and in the case of the Colorado River Basin, the demand has exceeded the overallocated water supply on a decadal basis since 2003 (Kenney et al. 2010; USBR 2012).

Confronting the reality of climate change and its potential impacts on water resources has been challenging for many water resource managers. Planning has traditionally been based on the period of instrumental record, and in many parts of the western United States, political sensitivities have inhibited a discussion of the impacts of climate change on water resources. Tree-ring reconstructions of streamflow have become an acceptable alternative, opening the door to considerations of time frames beyond the twentieth century, in the absence of open discussions of climate change (Woodhouse and Lukas 2006b; Rice et al. 2009). Management decisions based on the longer flow records can result in more resilient water supply systems for dealing with natural climate variability or anthropogenic climate change. The tree-ring reconstructions have become a stepping-stone, complement, or alternative to explicit projections of future hydrology, depending on needs and sensitivities of institutions.

The increasing use of tree-ring data in management has also come about in large part due to leadership from water resource professionals who are willing and able to grapple with new types of information for decision making, even if they are not required by the existing planning frameworks. This may reflect a more diverse training of water resource professionals. Key personnel at the Bureau of Reclamation (e.g., Prairie et al. 2008; Gangopadhyay et al. 2009), California Department of Water Resources, SRP (Phillips et al. 2009), Denver Water (Rice et al. 2009), and consulting firms (e.g., Harding 2005; Kenney et al. 2010) recognized the usefulness of tree-ring data and have been instrumental in the development of innovative techniques to apply these data to resource management. On the part of researchers, new sources of funding for decision-support science such as the National Oceanic and Atmospheric Administration (NOAA) Regional Integrated Sciences and Assessments (RISA) program and Reclamation's WaterSmart program have motivated collaborations between researchers and practitioners. On both sides, the emergence of researchers and practitioners serving as *information brokers*—people who understand both the scientific and management perspectives and challenges—has facilitated the use of scientific information in resource applications (Ferguson et al. 2014).

As new reconstructions have been generated for specific agencies and basins in the western United States, they have caught the attention of other water resource professionals, leading to requests for additional reconstructions. Since 2009, the ever-expanding West-wide network of over 60 gage reconstructions has been made accessible in a central location, along with supporting information, on the TreeFlow web resource (http://www.treeflow.info/). A series of over 15 workshops has facilitated the education of water managers and peer-to-peer interactions among practitioners who are interested in using the reconstructions (http://www.treeflow.info/workshops.html). With easier access to both the data and information about applications, over the past decade, a core group of paleo-savvy practitioners has evolved who are using tree-ring reconstructions in a variety of novel ways. This has provided case studies and motivation to other practitioners to consider the benefits of streamflow reconstructions in their planning process.

9.4 Challenges and Applications of Streamflow Reconstructions to Water Resource Management

In spite of the motivating circumstances cited previously, significant challenges exist to the application of streamflow reconstructions to water resource management. Fundamental mismatches between what is being produced by the scientific community and what is useful to the management community have hampered applications. For example, gages that could be most feasibly reconstructed by researchers were not necessarily those of interest to specific water agencies. Spatial coverage and timescales of the reconstructions (constrained to be annual, correlating to annual growth rings) have often not been compatible with an agency's water system's modeling or planning parameters (e.g., Woodhouse and Lukas 2006a). In addition, the capacity to make use of new types of information varies among water agencies, with some needs best met by relatively straightforward basic awareness raising, while others require specific model input to test system sensitivity over a range of conditions. Yet another challenge has been finding ways to translate the uncertainty in the reconstruction into the planning methodology. In recent years, many of these issues have been addressed in collaborations between researchers and water resource practitioners, leading to greater use of the streamflow reconstructions in water resource management. Several case studies that demonstrate the outcomes of these collaborations, in the South Platte River Basin and the Upper and Lower Colorado River Basins (Figure 9.3), are described next.

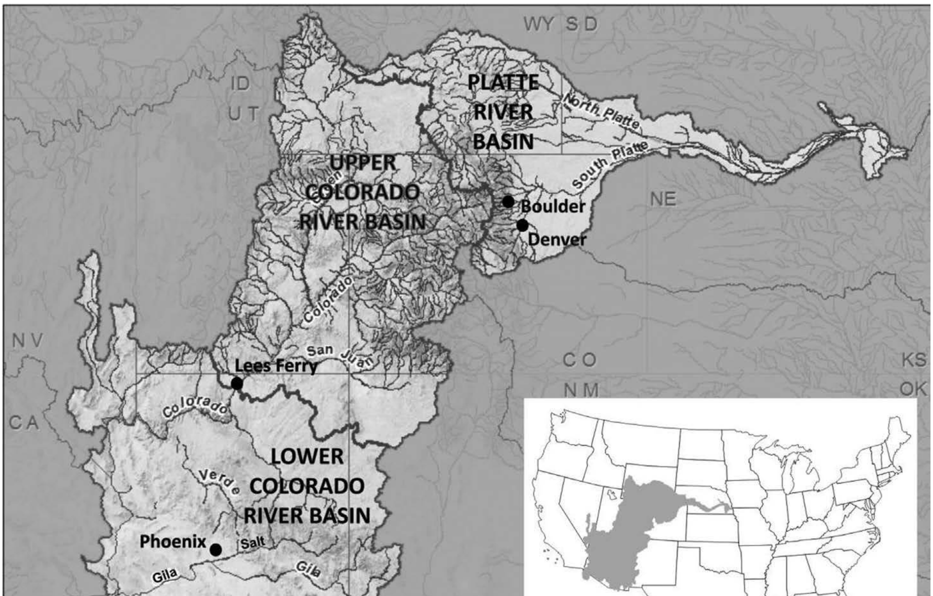

FIGURE 9.3
Rivers, basins, and cities mentioned in the case studies in this chapter.

9.4.1 Colorado Front Range Water Utilities: Stress-Testing Systems for Severe Drought and Climate Change

Colorado's Front Range region is home to over 80% of the state's 5.2 million residents. The several dozen municipal water utilities on the Front Range vary widely in their size, their technical capacity, and the makeup of their water supply portfolio. Starting around 1998, sustained engagement by tree-ring scientists based at NOAA and the University of Colorado (CU) in Boulder led to the use of tree-ring data in planning by several of these water providers. The work with two of these providers, Denver Water and the city of Boulder's Water Utilities Division, highlights the benefits and challenges inherent in the application of tree-ring data.

9.4.1.1 Denver Water

Denver Water is the oldest and largest urban water provider in Colorado, serving over 1.3 million people in Denver and the surrounding suburbs. About half of their water supply comes from the South Platte River Basin, in which Denver is located, and the other half from the Colorado River Basin (Figure 9.3), with two tunnels transporting water from the latter to the former. The impacts of droughts are buffered by 10 major reservoirs, located in both basins, which have a combined storage capacity of 670,000 acre-feet (830 million cubic meters [MCM]), equivalent to over 2 years of the current water demand.

Denver Water has developed a sophisticated model of its water system: the Platte and Colorado Simulation Model (PACSM), which simulates streamflows, reservoir operations, and water supplies in the South Platte and Colorado River basins. The model runs on input from 450 locations on a daily time step, using data from 1947 to 1991. The 1950s drought (1953–1956) had been considered the worst-case scenario for planning and still remains the most severe multiyear drought on record for Denver Water. In 2002, however, the third and most severe year of drought conditions led to record-low annual flows at several of Denver Water's gages, and raised concerns about the adequacy of the 1947–1991 model period as the baseline for planning.

After the Boulder-based tree-ring scientists developed preliminary reconstructions of their gages of interest, Denver Water funded the re-collection of about 20 tree-ring sites in both the South Platte and Colorado River basins to update the chronologies through 2002. The new streamflow reconstructions, generated in 2004 with the updated chronologies, very closely captured the drought conditions of 2002 (Woodhouse and Lukas 2006a). The fidelity of the trees in representing this recent extreme event enhanced the perceived credibility of the reconstructions by Denver Water's managers and board.

Using the new reconstructions as inputs to the PACSM system model faced major technical challenges—spatially and temporally disaggregating the tree-ring reconstructed values (annual, at two locations) to the daily time steps at 450 locations required by the model. The Denver Water engineers arrived at an "analog" method, in which the daily model inputs for each paleo year were derived from the year in their 1947–1991 model period that most closely matched the annual flow of that paleo year. The model inputs representing paleo years with higher or lower annual flows than any in this reference period were scaled up or down accordingly. Running the full tree-ring record (1634–2002) through PACSM, they could determine the impacts of the broader range of droughts seen in the paleorecord on their system under different assumptions of demand level and policy interventions during droughts. They found that a 4-year drought in the 1840s (1845–1848) and another one in the 1680s had greater modeled impacts than the 1950s drought but that their system would be able to meet water demands through the paleodroughts with progressive restrictions on outdoor water use.

While this was the most significant application of the tree-ring data by Denver Water, discussions between this engineering group and the tree-ring scientists over a period of 6 years led to other useful developments. For example, Denver Water was interested in reconstructing climate-driven variations in their water demand (i.e., outdoor watering) to complement the supply-side streamflow reconstructions. Variability in demand is influenced mainly by late spring and summer precipitation and temperature over the urban service area, while annual streamflow is driven by winter–spring precipitation over high-elevation catchments. These quantities are often related but in some years are well correlated. The reconstruction of water demand in the Denver Water service area allowed Denver Water to assess the frequency of periods with particularly high demand and low supply.

9.4.1.2 City of Boulder

The city of Boulder's Water Utility Division serves about one-tenth the number of customers as Denver Water. About 70% of its water supply comes from the Boulder Creek drainage in the South Platte River Basin, with the remainder coming from the Colorado River Basin via the Colorado–Big Thompson (C-BT) and Windy Gap projects (Smith et al. 2009). Boulder has ample annual average supply relative to the current demand of 25,000 acre-feet (31 MCM) but relatively less storage than Denver Water, equal to about 1 year of current demand, so their supply is vulnerable to severe multiyear drought. In addition to assessing this drought risk, Boulder has been ahead of the curve in considering how anthropogenic climate change might impact its water supply.

Collaboration between consultants for the city of Boulder and the NOAA and CU tree-ring scientists first led to a reconstruction of annual streamflows for Middle Boulder Creek from 1703 to 1987. As with Denver Water, the reconstructed flows were run through a system model to examine impacts on water deliveries and other metrics. Again, the multi-year drought from 1845 to 1848 was identified, along with another drought in the 1880s, as leading to greater stress on the system in terms of expected delivery reductions than any droughts in the twentieth century. These results were included in Boulder's comprehensive Drought Plan in 2003. At about this time, a separate simulated stress test of the city's system was performed, assuming a flat 15% reduction in annual streamflows due to climate change. The obvious next step was to assess the joint risks of climate variability—as more fully seen in the tree-ring record—and climate change, by examining what would happen if the droughts of the past occurred again under a warmer and possibly drier future climate.

Starting in 2006, Boulder conducted a multiyear study to assess the vulnerability of its water supply to climate change, with support from NOAA, CU, the National Center for Atmospheric Research (NCAR), and Stratus Consulting (Smith et al. 2009). The study was one of the very first to explicitly combine projected future climate from GCMs with paleoclimate reconstructions from tree rings. First, a new tree-ring reconstruction of annual streamflow for Boulder Creek, from 1566 to 2002, was generated using some of the same chronologies developed for the Denver Water work. A nonparametric *k*-nearest-neighbor technique was used to conditionally resample the 1953–2002 historic period climate, based on matching each paleo year with the five historic years that are nearest in terms of annual flow. The effect is similar to the Denver Water analog method in that it disaggregates the annual reconstructed streamflows, in this case, into monthly climate variables

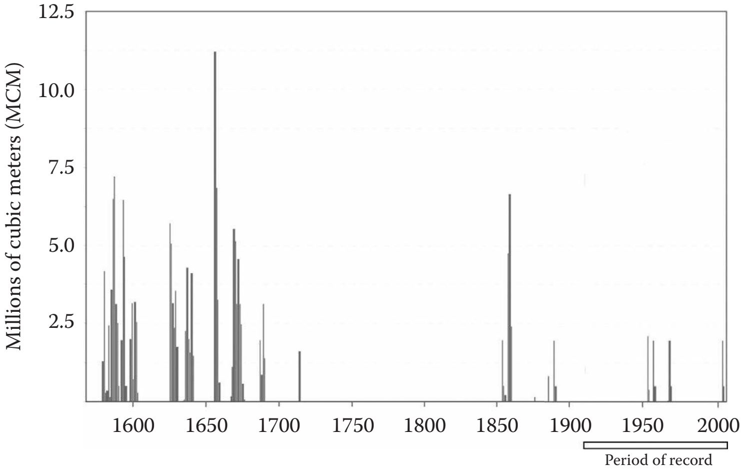

FIGURE 9.4
Modeled shortages in water deliveries by the city of Boulder, from simulation run that used temperature and precipitation changes from a global climate model (GCM) under the A2 (high) emissions scenario to adjust a 437-year (1566–2002) trace conditionally resampled from a tree-ring reconstruction of Boulder Creek. Using only the period of record for risk assessment (1907–2002) would dramatically underestimate the risk of shortage seen over the longer period. (From Smith, J.B. et al., The potential consequences of climate change for Boulder Colorado's water supplies, Stratus Consulting, for the NOAA Climate Programs Office. Boulder, CO, 2009.)

(precipitation and temperature). That allowed those variables to be separately adjusted according to the projected changes from nine different GCMs, and then input into snowmelt-runoff and water-balance models to produce multiple simulations conditioned on the paleodata and future climate conditions. The simulated Boulder Creek hydrology was then run through Boulder's water system model.

All of the system simulations showed that undesirable outcomes such as shortages in water deliveries tended to be concentrated in the 1600s and 1700s, when there were more frequent paleodroughts than in later centuries (Smith et al. 2009) (Figure 9.4). The frequency and size of those shortages also depended on the future changes seen in the particular GCM projection driving the simulation; the high-emissions (i.e., warmer) projections that also showed reduced precipitation had the most frequent and largest shortages, as would be expected. Overall, the combination of the tree-ring record and GCM output was more stressful to the system than either one alone.

9.4.2 Upper Colorado River Basin: Supply Scenarios Using Tree Rings

The Colorado River Basin covers over 240,000 mi.^{2} (620,000 km^2), including portions of Arizona, California, Nevada, Colorado, New Mexico, Utah, and Wyoming, collectively referred to as the *Basin States*, as well as northwestern Mexico (Figure 9.3). In the western United States, the Colorado River supplies water to about 40 million people, supports 3 million acres (1.2 million ha) of irrigated agriculture, and produces vital hydropower for the region. Two large reservoirs, Lakes Mead and Powell, account for the bulk of storage in the Colorado River system, which, combined, are able to store up to 60 million acre-feet (MAF), or 4 years of the twentieth-century average annual flow.

Two recent Bureau of Reclamation (hereafter *Reclamation*) planning efforts highlight the use of tree-ring data in Colorado River management. The first is an environmental impact statement (EIS) completed in 2007 in response to rapidly declining water levels during the early 2000s in Lakes Powell and Mead (USBR 2007, hereafter *FEIS*). This document provides important background and justification for the new operating policies developed to manage shortage and low reservoir conditions on the Colorado River. The second is the Colorado River Basin Water Supply and Demand Study, completed in 2012, arising from concerns regarding the reliability of Colorado River water supplies given the supply and demand imbalances that had persisted since the early 2000s (USBR 2012, Technical Report A; hereafter *Basin Study*). In contrast to the FEIS, the Basin Study did not inform any changes in policy but will undoubtedly serve as a rich source of information for future policy decisions.

Reclamation lists its collaboration with the University of Arizona, including tree-ring scientists, as one of the five key components in the research and development program that contributed to the analysis and content of FEIS (USBR 2007). Since 2004, Reclamation had been working with University of Arizona researchers in a project aimed at enhancing water supply reliability through improved understanding of reservoir system responses to natural and anthropogenic drivers. Identifying how tree-ring data could be used in Colorado River management was one of the primary objectives of this project. This objective was realized during the EIS process: tree-ring data were used to "analyze the sensitivity of the hydrologic resources to alternative future hydrologic scenarios" (USBR 2007, pp. 4–11).

9.4.2.1 Challenges of Integrating Tree-Ring Data into Reclamation's Management Model

Prior to using a streamflow reconstruction to conduct a sensitivity analysis in the FEIS, it was first necessary to address two issues: (1) reconstruction uncertainties and (2) the incongruity between spatial and temporal scales of the reconstruction and input requirements for Reclamation's management model. Several reconstructions have been developed for the Colorado River at Lees Ferry (e.g., Stockton and Jacoby 1976; Hidalgo et al. 2000; Woodhouse et al. 2006). A comparison of these reconstructions revealed that for any given year, there was a range of flow magnitudes. This uncertainty, however, was offset by the consistency among reconstructions of the hydrologic state information—whether it was a wet or dry period (Woodhouse et al. 2006). To address the uncertainty in the annual flow magnitudes, Reclamation developed a methodology that utilized state information from the reconstruction and magnitude information from the instrumental data (Prairie 2006). For each year in the reconstruction, conditional upon the state (wet or dry) of the current and previous year, a set of candidate years was identified in the instrumental record. From this set, one year was randomly selected and used to represent flow for that year. Blending the tree-ring and instrumental data in this way, it was possible to generate many different reconstruction-length sequences, each with novel sequences of instrumental data. Reclamation used both the blended (*paleo-conditioned*) and unblended tree-ring data to evaluate the Colorado River system.

The tree-ring reconstructions also needed to be disaggregated before they could be used for system analyses. Reclamation's management model required hydrological input at a monthly time step for 29 input locations within the basin, whereas Colorado River streamflow was reconstructed at an annual resolution for a single location in the basin, Lees Ferry. A nonparametric method was used to identify analog years in the instrumental record, enabling the disaggregation of the streamflow reconstruction into monthly data for multiple input locations. This approach was developed for the FEIS (Prairie 2006; Prairie et al. 2007). A similar methodology was used in the Basin Study (Nowak et al. 2010).

9.4.2.2 *Role and Use of Tree-Ring Data in Reclamation Studies*

The main findings in the FEIS were based on instrumental data used as input to Reclamation's system model. Tree-ring data were used to conduct a sensitivity analysis of the effect of hydrological inputs on system behavior because Reclamation considered it important to "…understand the potential effects of future inflow sequences outside the range of historic flows…" (USBR 2007, pp. 4–14). Thus, although results from the sensitivity analysis based, in part, on tree-ring data were not used in the primary evaluation of proposed actions, they did inform the Secretary of Interior's decision to designate the guidelines as *interim*, extending them only through 2026 (USBR 2007).

In contrast, for the Basin Study, tree-ring data played a central role in the primary analysis of evaluating system vulnerability and reliability. Here, Reclamation used four, equally weighted hydrological data sets to drive their system model: instrumental, unblended tree-ring, blended tree-ring, and downscaled projection. Thus, for any given evaluation of the Colorado River system, half of the supply scenarios were based either wholly or partly on tree-ring data.

While the role of tree-ring data in each planning effort was quite different, the use of tree-ring data was very similar. In both cases, tree-ring data provided multiple sequences of hydrological data for Reclamation to use as input for its management model. This generated an ensemble of outputs for any given system indicator, which was analyzed and evaluated in a variety of ways. By and large, the blended tree-ring data set tended to simulate more extreme outcomes for system indicators when compared to instrumental and unblended tree-ring data. For example, an FEIS analysis showed that by 2060, the tenth percentile of Lake Powell elevations simulated by blended tree-ring data was about 150 ft. lower than the tenth percentile of elevations simulated by instrumental and unblended tree-ring data sets (USBR 2007).

In the Basin Study, Reclamation examined how, in conjunction with multiple scenarios of demand and two management alternatives, the different supply scenarios affected system vulnerability over time (USBR 2012). In this analysis, each supply scenario contributed an equal number of input sequences, or traces. Vulnerability here was defined as the percentage of traces in which Lake Mead elevation was below 1000 ft. for any given month. In the short term, supply scenarios accounted for the greatest amount of variability in vulnerability, with instrumental (called *observed resampled* in the Basin Study) and unblended (called *paleo resampled* in the Basin Study) tree-ring data associated with the lowest vulnerabilities and downscaled projections with the highest vulnerabilities. By mid-century, however, vulnerability is largely governed by a combination of demand scenarios and management policy. For example, vulnerabilities based on instrumental data range from 0% to over 50% for all combinations of demand scenario and management alternative. A similar spread is indicated by the two tree-ring-based supply scenarios. However, within each supply scenario, there are differences in the relative vulnerability of each combination of demand scenario and management alternative. These results suggest that changes in demand scenario and operations guidelines alone, as illustrated by the blended tree-ring data, can increase the likelihood of Lake Mead levels dipping below 1000 ft., even without considering climate change projections (Figure 9.5).

9.4.3 Salt River Project—A Problem of Extremes: Integrating Tree-Ring Information into Water Resource Planning and Management

The SRP manages a 13,000 mi.^{2} (33,670 km^2) watershed area that includes dams, reservoirs, wells, canals, and irrigation infrastructure to supply water to its service area in the

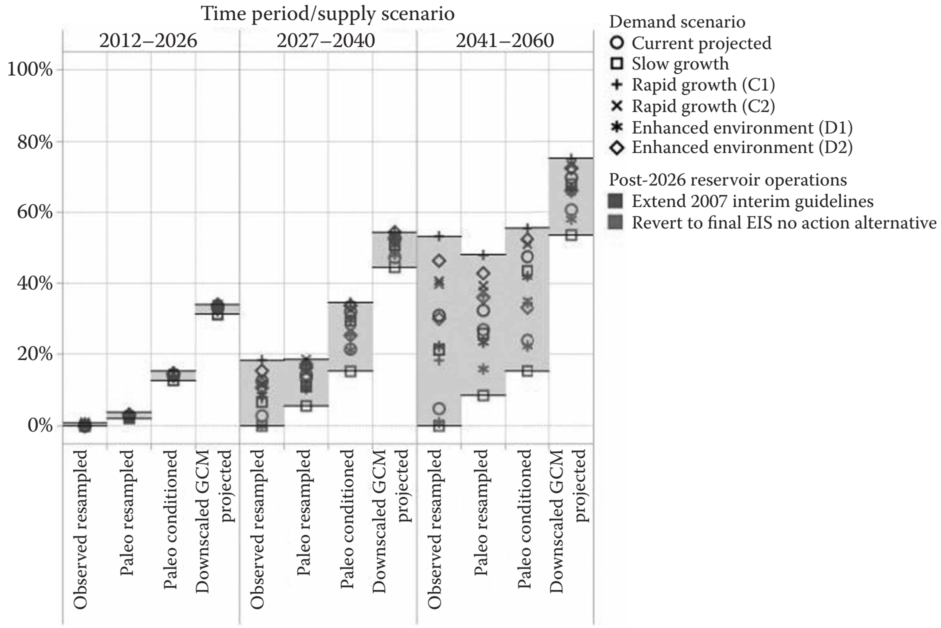

FIGURE 9.5
Percent of traces vulnerable without options and strategies by scenario and time period, Lake Mead elevation indicator metric (below 1000 ft. in any 1 month). (Figure from US Bureau of Reclamation's Colorado River Basin Water Supply and Demand Study, Final Report, December 2012.)

Phoenix Metropolitan Area (SRP 2014). Compared to Lake Mead, the amount of storage in the SRP reservoirs is small, resulting in a greater sensitivity to extreme high or low annual streamflow contributions originating in the Salt and Verde watersheds (Figure 9.3). A water exchange agreement with the Central Arizona Project (CAP), which delivers Upper Colorado River Basin (UCRB) water to Arizona, gives SRP an additional source of surface water, if needed. Such a need occurred in response to a multiyear drought that began in 1996 and by the end of 2003 had exceeded the historic 7-year drought of record for the SRP reservoir system. In fact, SRP's Roosevelt Reservoir would have been "close to empty" in 2002 without the CAP contributions of Colorado River water (Philips et al. 2009, p. 117). The severity of this event prompted a concern that extreme regional drought conditions might affect both Upper and Lower Colorado Basin water supply areas at the same time, presenting a major management challenge. To assess the probability of such an occurrence, SRP initiated a collaboration with the University of Arizona Laboratory of Tree-Ring Research to estimate the probability of synchronous extremes in the Upper Colorado and Salt–Verde River Basins using existing streamflow reconstructions from tree rings. The following section describes how the integration of paleoinformation into SRP's operational guidelines emerged from two studies, each focusing on a key planning and management question.

9.4.3.1 SRP I: Extreme Streamflow Episodes in the Upper Colorado and Salt–Verde River Basins

The SRP I study addressed the long-term synchrony of droughts and wet periods in the UCRB and Salt–Verde Basin, Arizona (Figure 9.3). The conventional view at the time of the study was that droughts in the Salt–Verde Basin would be buffered or offset by normal or above-normal supplies from the UCRB. Existing tree-ring chronologies were assembled and applied in multiple linear regression (Hirschboeck and Meko 2005) to generate reconstructions of total annual flow of the Colorado River at Lees Ferry and flow summed over the Salt, Verde, and Tonto Rivers (SVT). The former represents the Colorado River outflow from the UCRB, and the latter, the "local" river flow into SRP reservoirs in Arizona. Time-nested regression models (Meko 1997) explained up to 70% and 76% of annual flow for the SVT and the Colorado, respectively, and indicated that the tree-ring network was sufficiently dense for reliable inference of joint occurrences of high or low extreme flows over 1521–1964.

Dry years and wet years, or lows and highs, in the reconstructions were defined by the 25th and 75th percentiles of reconstructed flow for the common period. A count of events revealed that same-sign flow anomalies in the two basins occurred much more often than opposite-sign anomalies. Large opposite-sign events were found to be especially rare: in only 2 of the 444 reconstruction years was one basin below its 25th percentile, while the other was above its 75th percentile. The clear message from the reconstructions was that large flow deficits on the Salt–Verde are unlikely to be offset by high flows on the Colorado. Rather, extreme dry years or wet years were often shared by both basins. Synchronous lows, especially, tended to cluster in time, reflecting the occurrence of multiyear widespread drought conditions. Of interest from a management perspective was the observation that these extended low-flow periods could be interrupted by years of near-normal flow: the longest stretch of synchronous extreme dry years was three. Figure 9.6 depicts one of the longest clusters of synchronous low-flow years as revealed by counts in a 5-year moving time window.

9.4.3.2 SRP II: The Current Drought in Context

The main topic of the follow-up study was an assessment of the severity of the "current" drought (as of 2004) on the Salt–Verde as revealed by the long-term tree-ring record. This drought was judged at the time to have begun as early as 1996 and to have intensified during 1999–2004. Because this period postdated most of the previous collections of drought-sensitive chronologies in the Salt–Verde Basin, new tree-ring collections were needed. Accordingly, 14 tree-ring sites were collected in 2005, and the resulting chronologies were incorporated with existing data in a multivariate reconstruction model to generate a reconstruction of SVT annual flow, 1330–2005 (Meko and Hirschboeck 2008).

The results indicated that two of the current drought years—1996 and 2002—were unsurpassed in single-year severity of reconstructed drought since the fourteenth century. The long-term context of these exceptionally dry years is illustrated in a time-series plot of reconstructed flow (Figure 9.7). Despite these single-year anomalies, however, the multiyear severity of extended low streamflow during the current drought was not unprecedented. Running means of various lengths failed to identify this drought as exceptional. For example, the reconstructed running mean for 1999–2004 ranked 14th driest of all 6-year running means in the reconstruction. The two most severe multiyear events in the reconstruction were characterized by 5 consecutive years of flow below the long-term median, and both of these occurred in the distant past (Figure 9.7).

Throughout SRP I and SRP II, feedback from SRP scientific staff was important in guiding the research and often posed new questions. One question that arose concerned the length of the maximum interval of time between *drought-relieving* wet years in the reconstructed low flows. This information was deemed critically important by

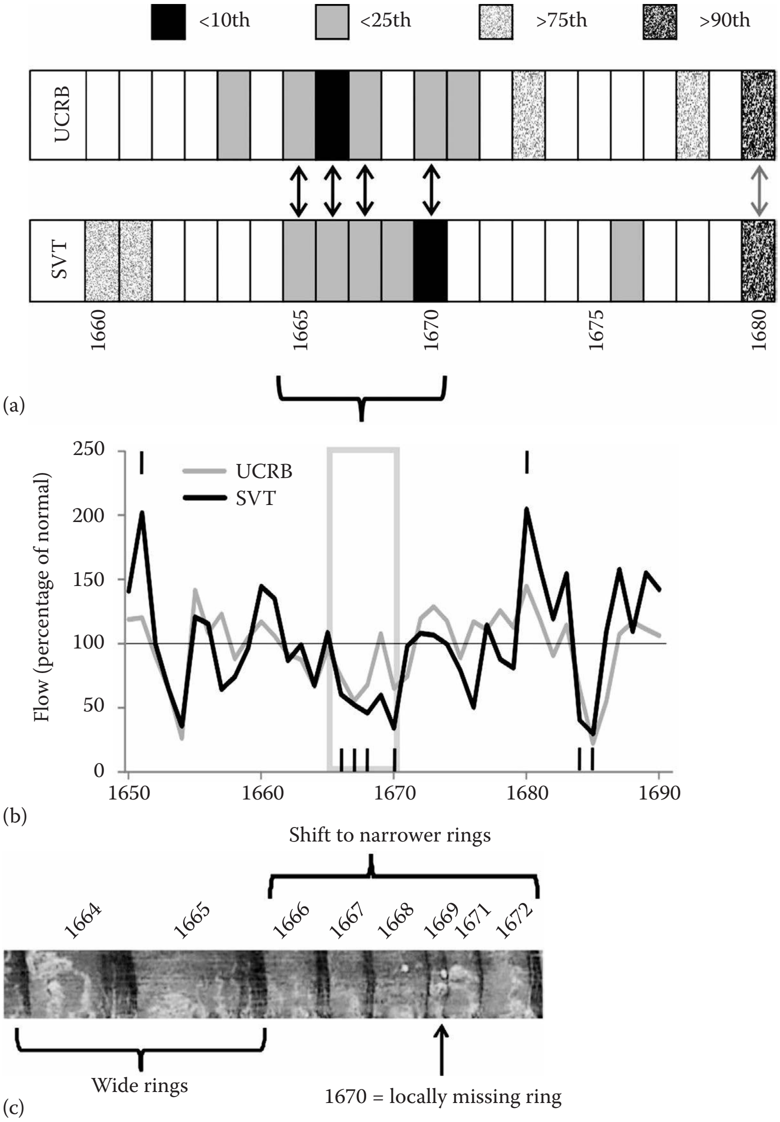

FIGURE 9.6
Synchrony of extreme low-flow years in the watersheds of the Upper Colorado River Basin (UCRB) and the Salt–Verde–Tonto River Basins (SVT) in the late 1600s. (a) Demarcation of high- and low-flow years in the UCRB and SVT tree-ring reconstructions based on percentiles of annual flow, 1660–1680. Synchrony between the basins in extreme low-flow years (<25th percentile) and extreme high-flow years (>75th percentile) is indicated by double-headed arrow. (b) Reconstructed flows for the period 1650–1690 are plotted as percentage of the 1521–1964 long-term mean. The moving window highlights four common dry years (ticks at bottom) during the 5-year period 1666–1670. High-flow years in common in both basins are marked by ticks at top. See text for description of reconstructions and definition of dry and wet years. (c) Tree-ring core segment from a site near Show Low, Arizona, in the Salt River watershed showing the narrow ring sequence during the 5-year period highlighted in (b). Growth during 1670 was so stressed that a complete ring did not form on this tree at the point sampled with the core.

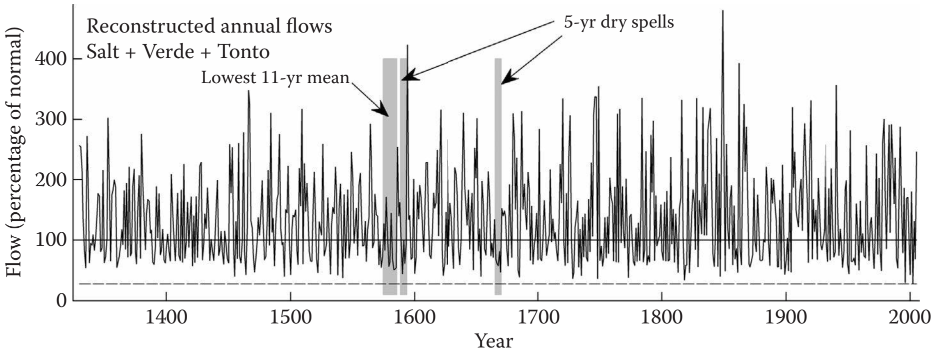

FIGURE 9.7
Time plot illustrating the long-term context of the 1996–2004 drought period near the start of the twenty-first century. Depicted are reconstructed annual flows summed over the Salt, Verde, and Tonto Rivers for the period 1330–2005. The dashed line shows an unprecedented single-year tree-ring-based low-flow response to the driest (2002) and next-driest (1996) years of recent drought. Shading marks the only two periods with flow below the long-term median for 5 consecutive years. The 5-year dry spell in the late 1600s is also shown in Figure 9.5. Normal (solid horizontal line) defined as median of 1914–2006 observed flows.

THE PALEORECORD AND FLOODS

The use of the paleorecord to transfer climate change information into operational flood hazard management presents substantially different challenges than those faced in employing the paleorecord in long-term planning for future low flow or drought extremes. Unlike droughts, which evolve from cumulative climatic conditions with an impact on tree growth that can be resolved in annual and seasonal tree-ring records, floods arise from distinct, watershed-specific precipitation events that do not appear as discrete features in the annual rings of tree growth.

Can Flood Events Be "Seen" in Streamflow Reconstructions? In watersheds where the maximum annual flood peak is well correlated with mean annual streamflow, inferences about the magnitude and frequency of past high flows (and presumed floods) can be made based on streamflow reconstructions, but the timing, frequency, and magnitude of the flooding that contributed to the high flow will be unknown, especially because reconstructions typically capture the magnitude of dry years better than wet years (see Figure 9.2 discussion). Floods produced by storms that contribute substantially to water supply are more likely to be correlated with high-flow years in a streamflow reconstruction than short-lived flash floods. However, years with high mean annual flow in either gaged or reconstructed time series do not always indicate major flooding. Reconstructed high-flow years may arise from sustained moderate flow, multiple floods of varying size, one or more long-lasting extreme events, snowmelt contributions unrelated to flooding, or other combinations of events.

"Paleo Flood Stage" Indicators. Floods in the pregaged record are best recorded by physical features in the environment that reveal past streamflow stages or the influence of high flows at or near the stream channel, such as botanical and geologic paleostage indicators or field evidence of exceedance or nonexceedance of a given

flood stage in the landscape (Baker 1987, 2008). Tree rings can serve as paleostage indicators when there is evidence of cell damage or alteration due to a flood event. Scars in rings caused by flood debris can indicate both stage and year of event, and changes in ring widths and cell or vessel size (e.g., "flood rings") can indicate timing and, in some cases, the stage of past events (St. George 2010). Such features are site specific, and flood scars are more likely to be found in small, high-gradient streams, but given the right kind of channel conditions, systematic field studies of alluvial stratigraphy (especially the detailed analysis of slack-water deposits) can provide excellent evidence of paleoflood stages throughout a watershed. Although the dating resolution varies when using non-tree-ring-based paleostage indicators to assess past flooding, with dating control and other supporting evidence, systematic field studies of paleoflood evidence can be combined with gaged data to augment records of naturally occurring extreme floods and serve as benchmarks for future flooding scenarios, including defining the upper bounds of physically plausible flood occurrence in a region (Enzel et al. 1993). Comprehensive overviews of various paleoflood approaches can be found in House et al. (2002) and Ballesteros-Cánovas et al. (2015).

Paleofloods and Flood Hazard Management. Global recognition of the importance of paleoflood information for flood risk assessment is increasing (Benito et al. 2004), although the integration of paleoflood methods into management practices has been hindered by policies that rely on standardized risk-assessment approaches (e.g., use of the *100-year flood*). To date, in the United States, the operational use of paleoflood information has generally been limited to dam safety applications that address flood hazards of extreme magnitude (US Bureau of Reclamation 1999; Levish 2002; Swain et al. 2006; Raff 2013). The need to provide flood hazard estimates for extremely large events has spawned innovative approaches that combine hydrometeorology, flood hydrology, and paleoflood hydrology to integrate physically based runoff modeling, stochastic and observed storm information, gaged streamflow, and paleoflood data (England et al. 2014). Other studies have used well-established hydraulic modeling and innovative flood-frequency analysis techniques applied to paleofloods to extend the gaged record, compute recurrence intervals, and estimate the magnitude and frequency of floods. An example of this latter approach for the western United States can be found in the work of Greenbaum et al. (2014), who used a 2000-year record of paleofloods to augment the systematic gaged flood record of the Upper Colorado River near Moab, Utah, and found that the gaged record "greatly underestimates the frequencies of extreme floods on a river that is critical to the water security of the nation."

SRP in view of their reservoirs' responsiveness to high flows; a single extreme wet year during a prolonged drought could refill a reservoir. The 676-year tree-ring record indicated that 3 years was the median interval between one or more drought-relieving years (defined as flow above the 75th percentile). The longest interval without relief was 22 years (1382–1403). In contrast, during the more recent 1913–2005 reconstructed record, the longest interval was 12 years. This length of interval occurred twice: 1953–1964 and 1993–2004. In sum, the message for SRP from these findings was that the drought they were currently managing was by no means unique in the context of the long-term tree-ring record.

Since the completion of the projects just described, SRP has made direct use of the SVT reconstruction from SRP II to quantitatively assess the robustness of the water supply system to droughts more severe than those of the instrumental period. The analysis tool for the assessment is SRP's storage planning diagram (SPD), a graph showing the relation between total reservoir storage, inflow, groundwater pumping production as a percentage of demand, and water allocation (Phillips et al. 2009). Applying this graph, SRP concluded that the unusually persistent 11-year tree-ring drought of 1575–1585, with an average flow of just 70% of the historical median, would severely stress the system under current operating rules but that the drought would be manageable with feasible changes to the allocation and pumping guidelines. Accordingly, in 2006, based on the tree-ring record, SRP's operational planning horizon was increased from 7 to 11 years. This appreciation for the long-term variability in the past has set the stage for additional adjustments in operating guidelines that may be necessary due to future climate changes.

9.5 Conclusions

Paleoclimate information from tree rings can assist the water management and policy community in planning for future risk—including that due to anthropogenic climate change—by providing a better understanding of natural climate variability on long time-scales. Knowledge of the range of natural variability possible is a useful baseline for planning, which also should include projected impacts of climate change. While the potential benefits of using tree-ring data in water resource management are widely appreciated, the actual application of these data to management has required considerable efforts on the parts of both researchers and water resource practitioners. In the case studies described in this chapter, the application of tree-ring data by agencies and institutions was facilitated by a number of factors. Water management organizations had sufficient technical capacity to engage with the new information, institutional prerogatives encouraged that engagement, and individuals within these organizations were willing and able to lead the effort to incorporate a new kind of data into their planning and management toolboxes. Researchers were interested in working outside the regular channels of academia, had the flexibility to do so, and were motivated by the potential application of research results into decision making. On both sides, and in all cases, the commitment of adequate time was also a factor, as the projects evolved in an iterative manner, built on multiple meetings over a period of several years.

Over time, the use of tree-ring data has made a difference in the way water resource planning in the western United States is framed. A paradigm shift has occurred, from relying on the gage record for planning and worst-case scenarios to considering the deeper past as documented in the tree-ring reconstructions. Understanding that natural climate variability includes a broader range of variability than contained in the twentieth- and twenty-first-century gage records has been an important step in beginning to plan more comprehensively for the future. The use of tree-ring data may also have opened the door to considering other types of data, including projections of future climate from GCMs.

Looking ahead, there is great potential to expand the use of tree-ring reconstructions to plan for and anticipate hydroclimatic events. New research methods combine tree-ring data and climate projections to assess future risks of extreme events (e.g., Ault et al. 2014). Other measures of climate important to water resource management such as temperatures, soil moisture, snowpack, and seasonal precipitation have been reconstructed or have the potential to be reconstructed, and work is underway to incorporate this information into management questions. Continued collaborations between researchers and water resource practitioners will be necessary to find ways to integrate relevant and useful results into water resource management, and to explore new uses, roles, and applications of these data to address important water resource issues.

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