Water Resource Management Informed by Paleohydrologic Data: An Example from the Colorado River Basin

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Abstract

Surface water supplies in many basins are becoming strained due to increasing demand, drought, and climate change impacts, particularly elevated temperatures. Now more than ever, water management requires information about hydroclimatic conditions beyond those recorded in the instrumental record, including the variability over past centuries, and the conditions that are expected in the future. In the Colorado River basin, tree-ring data are being applied in a variety of ways to understand the range of hydrologic variability possible. Paleohydrologic reconstructions of Colorado River flow are being used to assess the sensitivity of reservoir levels to sequences of flow during pre-historic droughts, evaluate the range of hydrologic variability being simulated from downscaled GCM output, and incorporate realistic frequency domain information into projected flows. These applications of paleohydrologic data from the Colorado River basin may be useful in other river basins experiencing similar stresses.

Key words: paleohydrology, Colorado River, water resource management

Introduction

Water resource management requires the best possible knowledge about the range of conditions that can be expected in the future. Historically, long-term (>1 year) operations and planning in water management have been based on the gaged hydrology, implicitly assuming hydrologic stationarity. However, it is increasingly recognized that the assumption of stationarity is faulty; the gaged hydrology in most basins does not capture the full range of potential hydrologic variability, and moreover, anthropogenic climate change is expected to shift the characteristics of future hydrology beyond the envelope of historic variability.

Resources to assist water managers in planning for and anticipating future conditions are currently being developed in the form of downscaled general circulation models to address regional climate projections more accurately, and the potential for seasonal to interannual forecasts is also being explored. Unfortunately, forecasts and projections at these longer times scales are either not skillful enough to be useful or are not currently available. Meanwhile, perhaps the most useful information presently available, at least for some areas, comes from the past. Examining relationships between climate, hydrology, and circulation provides an understanding of how the hydroclimatic system has behaved in the past and may be used as an analogue for what may occur in the future. When this understanding includes the use of precisely-dated and highly resolved paleohydrologic data, the range of conditions that may be used as analogues broadens considerably. The climate of the future may not necessarily be a replication of the past since humans are now having a discernible effect on climate in ways that they did not in the past. However, using the past as a baseline for the future, with the understanding that natural variability will be superimposed over anthropogenic climate change trends, may be a useful approach until forecasting and modeling skill improve.

In this paper, the Colorado River basin is used as an example to illustrate some of the ways in which paleohydrologic data are being applied to management questions and concerns. The Colorado River has long been a focus of tree-ring based reconstructions of streamflow, beginning with the first calibrated reconstruction of the upper Colorado River at the Lees Ferry gage by Stockton and Jacoby in 1976, which estimated annual flows from AD 1564-1961. Several efforts followed, using similar sets of tree-ring data but different statistical approaches and flow data for model calibration to reconstruct Colorado River flow at the same gage (e.g., Michaelsen et al. 1990, Hidalgo et al. 2000). More recently, updated tree-ring chronologies allowed for a longer calibration period and yielded two more upper Colorado River reconstructions, the longest dating from AD 762 – 2005 (Woodhouse et al. 2006, Meko et al. 2007). Similar work has focused on the lower Colorado River basin, resulting in reconstructions of Colorado River tributaries; the Salt, Gila, and Verde Rivers (Smith and Stockton 1981, Meko and Graybill 1995, Hirschboeck and Meko 2008).

This rich history of reconstructions in the Colorado River Basin has facilitated the integration of paleohydrologic data into water resource management. But the principal motivation for managers to consider and use the paleohydrologic data lies in the critical role the Colorado River plays as a water supply for southwestern North America, and the management challenges resulting from overallocation and the likely future decreases in runoff due to climate change (e.g., Milly et al 2005, Christensen and Lettenmaier 2006, Hoerling et al. 2009, USBR 2011). The main infrastructure features of the Colorado River include Lakes Powell and Mead, which together can store about four years of average annual flow (Rajagopalan et al. 2009). These large reservoirs are important buffers against the multiyear droughts that characterize the climate of this region, but the demands for water have recently matched the average annual inflows (Rajagopalan 2009). The increasing demand, in concert with projected decreases in runoff, have prompted water resource managers to consider a broad range of management tools, including paleohydrology, in planning for future water security.

Tree-ring reconstructions and implications for water resource management

Tree-ring data have been used to reconstruct past climate and hydrology for a number of regions, particularly in the arid to semi-arid western U.S. where many tree species are especially sensitive to moisture (e.g. Meko and Woodhouse 2011). These data have increasingly been used to inform water resource management, initially through qualitative implications. A primary use has been to provide a long-term context for assessing gaged hydrologic variability and to gain an awareness of the range of variability that has occurred over past centuries. The first example of this for the Colorado River occurred in the 1940s, when the Los Angeles Bureau of Power and Light was interested in assessing the power generation reliability at Hoover Dam, and commissioned a report on the hydrologic variability of the Colorado River documented by tree-ring data (Schulman 1945, Stockton and Jacoby 1976). In Stockton and Jacoby's 1976 report, they stated that because the long-term average flow documented in the Colorado River reconstruction was significantly lower than the average gaged flow, a supply and demand problem loomed in the near future (Stockton and Jacoby 1976). However, the years that followed the publication of their report were characterized by generally favorable climate conditions, and their warning was not taken seriously. In 1995, a major interdisciplinary research effort investigated the social, political, legal, and economic impacts of a severe sustained drought in the Colorado River basin (Young 1995). The severe sustained drought used for these studies was based on the worst drought in Stockton and Jacoby's (1976) reconstruction. The study results were published, again, during a period of above average flows, and were largely ignored by the water resource community (Harding 2005).

Tree-ring reconstructions and applications to water resource management

The last several decades of the 20th century were a period with only minor droughts but with accelerated growth in the regions supplied by Colorado River water (Nichols et al. 2001, Pielke and Doesken 2003, Woodhouse and Lukas 2006). Consequently, when a major drought did occur, starting in late 1999 and continuing through much of the 2000s, rivaling or exceeded the worst drought in the 20th century, its impacts were significant. This drought motivated questions by water managers concerning its unusualness and the frequency of droughts of similar magnitude; these were questions which could best be addressed with tree-ring data.

While the reconstructions of Colorado River flow have been used qualitatively to place drought events in a long-term context, more recently they have also been used in quantitative modeling applications. A number of water providers (in particular, Denver Water, Salt River Project, and Bureau of Reclamation) sought to quantify the impact of drought on their water system reservoirs and test management options for mitigating impacts of drought on water supply systems. A major challenge, however, in the quantitative application of tree-ring reconstructions to water resource management is the spatiotemporal mismatch between the tree-ring data (annual time steps, at one to several gages) and the input requirements for water system models (monthly or daily time steps, at tens to hundreds of input nodes). Several approaches have been developed to deal with this problem.

A relatively simple analogue method was developed to disaggregate the tree-ring data by engineers at Denver Water. Denver Water is the largest urban water provider in Colorado and uses water supplies from both the upper Colorado and South Platte Rivers. Their analogue method matched each year in the reconstruction with the most similar year in the hydrologic data set for which daily model data were available (Woodhouse and Lukas 2006). The daily data for that year were then applied to the reconstruction year, with paleo-years higher or lower than any in the gage record being scaled as appropriate. This was done for each of 450 input nodes using the Colorado River or the South Platte River reconstructions, depending on the location of the node. The water supply model was then run on the paleohyrologic data, extending back to 1650.

A different approach to the space/time disaggregation of the tree-ring data was developed for the Bureau of Reclamation's Colorado River Simulation System (CRSS) model which is used for long-term planning. The Bureau of Reclamation is the US government agency charged with managing and operating most of the Colorado River's reservoirs, maintaining river channels, and planning to meet current and future water supply needs. Prairie et al. (2007) developed a non-parametric approach to disaggregate annual flow values at a single node, to the monthly time steps and 29 input nodes required by the CRSS model. The temporal disaggregation is performed first, then the spatial disaggregation, using a K-nearest-neighbor approach with a conditional probability density function to simulate flow values (Prairie et al. 2007). This space/time disaggregation method was developed and tested with instrumental data and applied to the reconstruction of Colorado River flow so that CRSS could be run with the 1200 years of reconstructed flows developed by Meko et al. (2007).

After this numerical hurdle was overcome, Reclamation and its partners have gone on to apply the reconstructed flows in several different ways. Ironically, the large number of reconstructions that have been generated for the Colorado River has cast some doubt on the reliability of the reconstructions. Differences in the reconstruction values arise from differences in the tree-ring data, natural flow data, and statistical methods used for reconstructions. As a result, the magnitudes of the flows vary somewhat, while the state information (the sequences of wet and dry) is more consistent. Thus, Reclamation engineers initially felt the state information (flow sequences) was more reliable, and developed a method to combine this information in the reconstruction with the specific flow magnitudes from the gage record to produce "paleoconditioned" flows (Prairie et al. 2008). This process resulted in a richer sequence of flows, including long runs of low flows, than are contained in the gage record. The paleo-conditioned flows have been used to create scenarios for risk analysis and reliability assessment. One important example of this is the application of the paleoconditioned data for a sensitivity analysis used in the development of Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead (USBR 2007). Both the tree-ring reconstruction of Colorado River flow (which they termed "direct paleo")and the paleoconditioned flows were used to assess the impacts of different management strategies on the Colorado River system, using the a prolonged drought of the 12th century as a worst-case scenario (Prairie et al. 2008, USBR 2007).

Another example of the application of the space/time disaggregated Colorado River reconstruction has been to evaluate the response of reservoir levels to the worst drought scenarios from the Meko et al. (2007) Colorado River reconstruction. In this case, an ensemble of the fifty 25-year runs with the lowest average flows were run through the CRSS model to assess the response of Lake Mead levels (Meko et al. 2010). The behavior of Lake Mead during drought is of particular interest because new management guidelines include shortage triggers tied to Lake Mead levels (USBR 2007). Similar work has assessed the probability of triggering shortages using CRSS and the Colorado River reconstruction (Morino and Bark 2010).

The tree-ring reconstruction of Colorado River flow (Meko et al. 2007) was also used as the basis to examine shifts in mean, interannual variability, and persistence in runoff, and to assess the relative importance of these characteristics in determining thresholds and requirement for reservoir storage needs based on current demand at a given level of reliability (Jain and Eischeid 2008). This information has not yet been directly applied to management, but it has important implications for assumptions of non-stationarity and reliance on the length-limited gage record for long-term planning.

While previous examples are for the upper Colorado River basin, tree-ring reconstructions have also been applied to the water resource management on the tributaries in the lower Colorado River basin. The Salt River Project (SRP) is a large, semi-private water provider in the Phoenix area, responsible for serving urban and agricultural water needs as well as providing hydropower. SRP recently used reconstructions of the major lower

Colorado River basin tributaries, the Salt and Gila Rivers, to assess their vulnerability to prolonged drought. SRP used the reconstructions to establish a new worst-case scenario, in terms of drought duration, and to test strategies for the management of surface water supplies from both the upper and lower Colorado River basins and from local groundwater (Phillips et al. 2009). The drought duration documented in the tree-ring reconstruction prompted SRP to alter their operational guidelines so that a long-term 10% reduction in flows would not lead to depleted surface water supplies (Phillips et al. 2009).

Reconstructions of past flow and future climate change

The application of Colorado River reconstructions to water resource management in the examples above indicate water supply response to worst-case droughts in the past, events that could be repeated in the future under conditions natural climate variability alone. Implicit in some of these applications are the impacts of climate change on Colorado River water supplies, with the recognition that drought conditions could be even worse in the future, exacerbated by warmer temperatures and possibly declining precipitation (e.g. McCabe and Wolock 2007, Barnett and Pierce 2009, Phillips et al. 2009, Gangopadhyay and McCabe 2010).

Combining the long-term natural variability in streamflow from the tree-ring based reconstructions in concert with climate change projections is an approach that is being utilized in several different ways. One of these approaches targets immediate applications to water resource management, while the others have implications for water resource management, if not direct applications. A proof-of-concept study explored methods for combining information from tree-ring reconstructions, gage data, and flows based on climate change projections for the Gunnison (a major tributary of the Colorado River) and upper Missouri Rivers. Four types of flow scenarios were generated based on different planning assumptions about water supply variability, and their usefulness for hydrologic planning was evaluated (USBR 2009). The study authors recommended that a blend of all three types of information (reconstructed flows, gaged flows, and projected flows) may be desirable if the reconstructed flows contained frequency information different from that in the climate projections, as was the case for the Missouri River. In the Gunnison, surpluses (wet runs of years) documented in the reconstruction were not replicated in the climate changes projections, while deficits (dry year runs) were adequately represented.

Several other studies have used non-operational water supply models to test the sensitivity of the Colorado River system to climate change impacts. In the strictest sense, the results of these studies are not directly applicable to management since they do not incorporate all functions of an operational system model. These studies can provide management agencies with information that may motivate research with operational models. Several of these studies use tree-ring reconstructions of Colorado River flow to test generalized climate change scenarios under a broader range of conditions than provided by the gage record, or to incorporate natural low-frequency flow variability, which is often lacking in climate change projections.

Barnett and Pierce (2009) used a simple water budget model for the Colorado River to examine the impacts of climate change on water deliveries under several different scenarios over the next 50 years. They suggest that impacts from flow reductions of 10% and 20%, based on 20^{th} century mean flows could be mitigated through reduced water deliveries. However using the long-term mean of flow averaged across all published Colorado River tree-ring reconstructions (considerably lower than the 20^{th} century mean) as the baseline for the model resulted in the need to almost immediately reduce deliveries, and with further reductions in flow from climate change, adequate reductions in deliveries are not likely to be feasible (Barnett and Pierce 2009).

Rajagopalan et al. (2009) took a slightly different approach in assessing Colorado River response to climate change. They quantify the risk of water supply depletion based a set of growth, management, and climate change scenarios. A water balance model which incorporates realistic storage, inflows, outflows, and evaporation, runs on natural streamflow variability from a blend of tree-ring reconstructed and historical flows (Prairie et al. 2008). As in Barnett and Pierce (2009), reductions in flow of 10% and 20% over a 50-year period were considered. Their results indicated that a 10% reduction was likely to result in a low risk of reservoir depletion but a 20% reduction would produce a significantly increased risk. However, they determined that flexibility in management (i.e., reductions in deliveries, and different shortage criteria) could mitigate some of this risk.

Summary and conclusions

Reconstructions of streamflow from tree rings have increasingly been used to inform water resource management. Examples of some of these applications are cited above, and others can be found at http://treeflow.info. Long reconstructions of streamflow have been used in a variety of ways, from providing an awareness of the range of hydrologic variability possible, to an assessment of worst-case droughts, and as input into water operations models to assess the robustness of water systems under the most severe droughts of past centuries (e.g. USBR 2007, Phillips et al. 2009, Rice et al. 2009). Colorado River reconstructions contain a more complete characterization of hydrologic variability than the gage record alone, and provide a baseline upon which the impacts of anthropogenic climate change will be imposed (e.g. McCabe and Wolock 2008, Gangopadhyay and McCabe 2010). Water resource managers in the Colorado River basin have begun to incorporate both the natural variability more fully expressed in the tree-ring reconstructions, and effects of climate change, into planning in order to effectively balance supply and demand in the future. Multiple scenarios that include both paleohydrologic and climate change information may provide a more robust basis for decision making. The methods and applications of tree-ring reconstructions to water resource management presented here can be applied in other basins where reconstructions exist (or where there is the potential to develop reconstructions).

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