~ENHANCING WATER SUPPLY RELIABILITY~

An interdisciplinary research project to enhance predictive capacity on the Colorado River

Annual Report, Phase III
June 2011

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Memorandum

To: RUSS CALLEJO, CIVIL ENGINEER, CADSWES, RECLAMATION
GUSTAVO CHAVARRIA, GRANTS OFFICER, PHOENIX AREA OFFICE, RECLAMATION

FROM: KIYOMI MORINO, ON BEHALF OF BONNIE COLBY, DAVE MEKO, PETER TROCH AND CONNIE WOODHOUSE, UNIVERSITY OF ARIZONA

DATE: June 29, 2011

RE: ANNUAL REPORT, PHASE III
ENHANCING WATER SUPPLY RELIABILITY PROJECT

The enclosed materials constitute the annual report for Phase III of the University of Arizona – Reclamation, *Enhancing Water Supply Reliability* study. This ongoing collaboration has brought together an interdisciplinary team that is finding new ways to work together with the end goal to inform better management of water supply risks to end-users in the Lower Colorado River Basin through improved understanding of hydrologic variability, better predictive skills, and management of supply risk. The project has contributed to the education of six Master's students[1] and four PhD students[2] over the lifetime of the project and supports two postdocs[3]. Since the last report a number of high-quality products have been developed, including academic manuscripts and guidebooks. Equally important is the ongoing collaboration between Reclamation staff and the University of Arizona faculty, postdoctoral research associates and graduate students.

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[1] Masters degrees have been awarded to: Katie Pittenger MSC 2006 (Agricultural and Resource Economics); Lana Jones MSc 2008 (Agricultural and Resource Economics); Michael O'Donnell MSc 2010 (Agricultural and Resource Economics); Laura Lindenmeyer MSc 2006 (Hydrology); Matthew Switanek MSc 2008 (Hydrology); and Rachel Beagles MSc 2011 (Hydrology).

[2] PhD degrees have been awarded to: Scott St. George PhD 2007 (Geosciences); Kiyomi Morino PhD 2008 (Geography); Dustin Garrick PhD 2010 (Geography); and Matthew Switanek PhD expected 2011 (Hydrology).

[3] Post-doctoral Research Associates include: Dr. Rosalind Bark (water policy and economics) and Dr. Kiyomi Morino (dendrochronology).

Research Update

For the period April 2010 through March 2011

This progress report outlines the progress in Phase III made for the period April 2010 through March 2011. In addition to the disciplinary efforts described below, interdisciplinary efforts have continued with the collaborative efforts of Rosalind Bark and Kiyomi Morino. Building from previous work in using paleodata to represent climate change scenarios and force CRSS, Kiyomi and Rosalind have initiated research that considers various stakeholder options to climate change impacts. This work was presented at the annual conference for the American Meteorological Society in January 2011.

Economics Sub-group.

The economics sub-group, of Dr. Bonnie Colby, Elizabeth Schuster and Michael O'Donnell, focused on publishing the research and preparation of stakeholder materials on innovative transfer mechanisms to enhance supply reliability for urban and habitat water needs in the Lower Colorado River Basin. This year, three peer-reviewed journal articles and three book chapters outline water transactions and forebearance as approaches to managing risk under climate change.

Paleo-hydrology Sub-groups

There are two paleohydrology sub-groups. Group 1 is comprised of Dr. Dave Meko (DM) and Dr. Kiyomi Morino (KM) and Group 2 includes Dr. Connie Woodhouse (CW), Dr. Mary Glueck (MG) and Brewster Malevich (BM). In Group 1, the team of DM and KM has focused on three areas: 1) characterizing spatial patterns of paleo-hydrological variability; 2) Lower Basin streamflow reconstructions; and 3) CRSS applications. In the first area of focus, principle component analysis of moisture-sensitive tree-ring chronologies in and around the target sub-basins in the Lower Basin (Bill Williams, Virgin, Kanab, Paria, and Little Colorado) suggest a north(-west)-south(-east) dipole for the target basins. Preliminary analysis suggests that this contrast might be driven by a small subset of years (~14% of the years analyzed) where the north (south) end of the region experiences above (below) average moisture while the south (north) end of the region experiences below (above) average moisture. In the second area of focus, work on streamflow reconstructions for the target sub-basins in the Lower Basin continues along two fronts. Along the first front, at least 8 new/updated tree-ring sites have been leveraged from the North American Monsoon project (PI's include Meko and Woodhouse). New/updated collections are also scheduled for late spring/summer of 2011. Along the second front, analysis of Reclamation's Consumptive Uses and Losses reports (for the Lower Basin) and USGS water use data revealed some formidable challenges in computing naturalized flows. Currently, various statistical methods are being explored to estimate natural flows. And finally, paleodata has been deployed in two instances to force CRSS and generate scenarios of potential climate change impacts. In the first case, a generalized representation of system response has been developed in the form of a response surface. Results indicate the importance of maintaining a positive net supply. For deficits as large as 1 maf, there can be severe consequences for deliveries and power generation even for an initial Lake Mead elevation as high as 1150 ft. In the second case, a subset of 25-yr sequences with the lowest mean streamflow were input into CRSS to construct an ensemble of worst-case scenarios. This analysis was included in study examining uncertainties in tree-ring reconstructions of streamflow (see Appendix A, Meko et al *in press*).

In group 2 (CW, MG & BM), research efforts have focused on the development of a "catalog" of upper Colorado River basin (CRB) droughts for the period of the gage record. The purpose here has been to develop a basic understanding of the character of CRB droughts and the ocean/atmospheric conditions that accompanied them. Droughts are defined as consecutive years below the 1906-2006 Lees Ferry water year flow average unbroken by less than two consecutive years above average. Using these criteria, seven droughts were defined. We have dropped the shortest, a 4-yr drought in the 1940s, leaving six droughts to analyze. For each drought, we have documented seasonal (based on three seasons, O-F, MAM, J-S) precipitation and temperature, spatial patterns of precipitation, and sequences of flow years. In order to investigate possible causal mechanisms, we have compiled maps of sea surface temperatures and 500 mb geopotential heights to characterize the state of the ocean/atmosphere system during CRB droughts. We have also compiled circulation indices for the Tropical and North Pacific, Indian Ocean, Atlantic Ocean, and northern Hemisphere to gain insights on the coincidence of modes of circulation during periods of drought.

This study has been largely descriptive, but results suggest that while each drought is different, there are a range of features that may result in drought. El Niño/Southern Oscillation (ENSO) is definitely a player, and cool or La Niña events were largely responsible for the 1950s drought conditions, but ENSO seems to have been less responsible for other droughts. In addition, in some years, warm ENSO or El Niño events correspond to drought, indicating the basin is behaving like the northern Rockies/Pacific Northwest region. The transitional nature of the CRB with respect to ENSO is obvious, but it also appears that this region is sensitive to the way that the Aleutian Low is positioned, particularly with respect to a center of high pressure over western North America. These are two centers of action in the Northern Hemisphere circulation patterns known as the Pacific North American (PNA) patterns, which is largely responsible for the path the wintertime jet stream takes and the delivery of moisture across this region. The CRB and its position between two dipole centers linked to ENSO was the topic of an invited AGU presentation in December. I will be working on a publication this fall on the droughts and the transition zone. A summary report is currently being generated and a peer-reviewed publication is planned for the next year.

Hydrology Sub-group

In the hydrology sub-group, research has been conducted by Matthew Switanek and Rachel Lambeth-Beagles under the direction of Dr. Peter Troch. In Matt's research, the potential of decadal predictability was explored in the Colorado River basin. The Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO) climate indices have been used extensively in a variety of hydroclimate analyses to investigate decadal predictability of regional climate and water cycle dynamics. One such example shows a strong relationship between the phases of these indices and streamflow at Lee's Ferry along the Colorado River (McCabe et al. 2007). With this apparent connection, there is an implication that these indices could be used to forecast the next decade of streamflow at Lee's Ferry. In this study, PDO and AMO were used to make retrospective forecasts of the 40 most recent ten year running means of Lee's Ferry streamflow and were found to explain 45% of the observed variance ($p<.01$). Next, we tested whether or not this relationship, and the accompanying forecast skill, has been consistent over a longer period of time than the observed record. Existing reconstructions of PDO, AMO and Lee's Ferry streamflow were used to find that the forecast skill over the reconstructed periods has rarely been as high as what is seen in the observed record. Based on a wavelet analysis, the three time series all share a dominant multidecadal frequency between 40 and 70 years in length. This might help to explain the skill that is seen in the observed record. However, this multidecadal frequency is not persistent in time for any of the reconstructed time series. Therefore, decadal predictions at Lee's Ferry may prove to be more difficult than the observed record suggests. This work has been submitted to Geophysical Research Letters.

During the past year, Rachel completed her Master's Thesis research. The main question driving this research was, "What are the drivers of annual to decadal streamflow variability in the lower Colorado River Basin?" Streamflow, temperature and precipitation were analyzed for past trends and patterns. An understanding of how these variables have interacted in the past will provide useful information in identifying predictive capacity for the lower CRB. The four sub-basins in the lower CRB were selected based on their contribution to lower Colorado River streamflow: the Paria, Little Colorado River, Virgin/Muddy, and the Bill Williams. Three of the four basins empty into the Colorado River between Lake Powell and Lake Mead. Their contribution to the total flow of the river can affect the amount of water released from Lake Powell. Only the Bill Williams is downstream from Lake Mead. It is still of interest as its contribution can affect releases from upstream reservoirs. Annual streamflow, temperature, and precipitation data for the four basins was compiled over a common period of 1906-2007. Gage data for streamflow was obtained from the Bureau of Reclamation. PRISM (Parameter-elevation Regressions on Independent Slopes Model) data for temperature and precipitation is available publicly from the University of Washington. Results indicate that over the past 102 years there is no statistically significant trend in precipitation. There is, however, a strong positive trend in mean, max and min temperatures. A negative trend was found in streamflow for all but one of the four basins. No conclusions have been drawn about why no trend has been detected in the Virgin/Muddy streamflow. Although no trend was evident in the precipitation data the positive association through time between streamflow and precipitation is statistically significant for all tributaries. Except for the Paria, the negative association between mean temperatures and streamflow and maximum temperature and streamflow are also significant. Minimum temperature and streamflow do not appear to be statistically dependent upon one another. We draw two major conclusions from this statistical analysis. First, on an annual scale, variability in precipitation will be the dominant predictor of streamflow variability. When the trend in temperature is removed, temperature variability on an annual scale does not predict a significant portion of streamflow variability despite the fact that both max and mean temperatures are negatively associated with streamflow. And secondly, over time the upward trend in temperature is reflected in a downward trend in streamflow. Converting this influence into a meaningful metric has yet to be done; however, it appears that when the trends in temperature and streamflow are considered, temperature's influence on steamflow values becomes statistically significant.

Project Deliverables: A summary

For the period April 2010 through March 2011

The deliverables of this project include a number of manuscripts published in leading journals, posters and presentations made at academic meetings, and book chapters. Products denoted by "*" can be found in Appendix A. All materials listed below, including PowerPoint presentations, can be provided in pdf format upon request.

Publications

Journal articles

Basta, E. and **B. Colby**. 2010. Water Market Trends: Transactions, Quantities, and Prices. *The Appraisal Journal* 78(1):50-66.

* **Jones, L**. and **B. Colby**. 2010. Weather, Climate, and Environmental Water Transactions. *Weather, Climate, and Society* 2: 210 – 223.

* **Meko, D.M. C.A. Woodhouse**, and **K. Morino**. 2011. Dendrochronology and links to streamflow. Submitted to *Journal of Hydrology* doi:10.1016/j.jhydrol.2010.11.041.

Switanek, M.B. and **P.A. Troch** 2011. Changes in decadal prediction skill for Colorado River streamflow using observed and reconstructed ocean-atmosphere teleconnections, submitted to Geophysical Research Letters.

*** Woodhouse, C.A.**, **D.M. Meko**, G.M. MacDonald, D.W. Stahle, and E.R. Cook. 2010. A 1,200-year perspective of 21st century drought in southwestern North America. Proceedings of the National Academy of Sciences 107(50):21283-21288.

Book chapters

Colby, B., E. Basta, and K. Pittenger, 2011. Temporary Water Transactions and Climate Change Adaptation, Chapter 2 in *Risk and Resilience: The Economics Of Climate-Water-Energy Challenges In The Arid Southwest*, Editors B. Colby and G. Frisvold, Resources for the Future Press.

Colby, B., **L. Jones** and K. Pittenger, 2011. Economic Tools For Climate Adaptation: Water Transaction Price Negotiations, Chapter 4 in *Risk and Resilience: The Economics Of Climate-Water-Energy Challenges In The Arid Southwest*, Editors B. Colby and G. Frisvold, Resources for the Future Press.

Bark, R.H. and **B. Colby**, 2011. Climate, Changing Snowpack and the Economics of Winter Recreation, Chapter 11 in *Risk and Resilience: The Economics Of Climate-Water-Energy Challenges In The Arid Southwest*, Editors B. Colby and G. Frisvold, Resource for the Future Press.

Theses and Dissertations

O'Donnell, M. 2010. *Innovative Water Supply Reliability Arrangements*. Master's Thesis, Department of Agricultural and Resource Economics, University of Arizona, Tucson, AZ.

Other

Jones, L. and **B. Colby**, "Farmer Participation in Temporary Irrigation Forbearance: Portfolio Risk Management, *Western Regional Development Centre Rural Connections*, May, 2010.

Workshops

In October 2010, the University of Arizona hosted the Colorado River Hydrology Working Group Meeting.

Presentations & Posters

Colby, B. 2010. "Innovations in Climate Adaptation for Water Supply Managers", Walton Foundation Workshop, August. PRESENTATION.

Bark, R. and **K. Morino**. 2011. Drought management in the Lower Colorado River Basin: Combining paleo-streamflow ensembles, CRSS & decision trees. American Meteorological Society, Seattle, WA, January 22-27. POSTER.

Lambeth-Beagles, R.S., Troch, P.A., and **M.B. Switanek** (2010) A look at history for improved future streamflow predictions in the Lower Colorado River basin. American Geophysical Union, San Francisco, CA, December 13-17. POSTER.

Malevich. S.B. 2010. Updating the 12-year CPR for the Colorado River basin. Colorado River/ Reclamation Working Group Meeting, University of Arizona, Tucson, AZ October 13-14. PRESENTATION.

Morino, K. and **R. Bark**. 2010. Climate change and the innovative use of tree-ring reconstructed Colorado River streamflow. Arizona Hydrological Society, Tucson, AZ, September 1-4. PRESENTATION.

Morino, K. and **R. Bark**. 2010. Characterizing uncertainties in water availability in the Colorado River system using response surfaces. American Geophysical Union, San Francisco, CA, December 13-17. PRESENTATION.

Switanek, M.B. and **P.A. Troch** (2010) Decadal predictability in the Colorado River basin. American Geophysical Union, San Francisco, CA, December 13-17. POSTER.

Woodhouse, C.A. and **M.F. Glueck**. 2010. A Catalogue of Upper Colorado River Basin Droughts. Colorado River/ Reclamation Working Group Meeting, University of Arizona, Tucson, AZ October 13-14. PRESENTATION.

Woodhouse, C.A. and **M.F. Glueck**. 2010. A Catalogue of Upper Colorado River Basin Droughts. American Geophysical Union, San Francisco, CA, December 13-17. PRESENTATION.

Other presentations on the CO River

Woodhouse, C.A. Hydrologic Variability in the Upper Colorado River Basin over the Past 1300 Years. 2011 Tamarisk Research Conference, Tucson, AZ, 16-17 February, 2011.

Woodhouse, C.A. Tree-Ring Reconstructions of Streamflow and Drought: Lessons from the Past for Future Planning. Climate Change Adaptation Workshop, Santa Fe and Carson National Forests. Abiquiu, NM, January 27, 2011.

Woodhouse, C.A., J.L. Russell, E.R. Cook. North American Drought Dipole and its Influence on Colorado River Flow. 2010. American Geophysical Union, San Francisco, CA, 13-17 December 2010.

Woodhouse, C.A. Tree Rings and Water Resource Management: Colorado River Examples and Potential for the Indus River. 2nd International Conference Dendrochronology, Federal Urdu University of Arts, Science and Technology, Annual Karachi, Pakistan, November 15, 2010.

Woodhouse, C.A., J.J. Lukas, K.K.Hirschboeck, **D.M. Meko**, and J.L. Rice. Dendrohydrology: A Tool for Decision Making in the Face of Climate Uncertainty. World Dendro Conference, Rovaniemi, Finland. June 14-18, 2010.

Media Coverage

Jensen, M. N., Expectations for the Southwest: Hot with decades of drought. UANews, December 13, 2010. http://uanews.org/node/36114

Honors

Peter A. Troch received the Dalton Medal 2011 from the European Geosciences Union (EGU) for seminal contributions to hydrology reviewed as an Earth science.

Matt B. Switanek received a GIGA (Graduate Incentive for Growth Awards) scholarship to support his research in hydrometeorolgy.

Project Leveraging

Connie Woodhouse: Climate Assessment for the Southwest (CLIMAS) program, a NOAA-funded project at the University of Arizona that links science with stakeholders; Western Water Assessment (WWA) program, a NOAA-funded project at the University of Colorado that links science with stakeholders; NSF-funded North American Monsoon project: shared chronology collection and development for both projects. **Dave Meko**: NSF-Funded North American Monsoon project: shared chronology collection and development for both projects. **Peter Troch**: City of Phoenix, CAP, Salt River Project funding to explore water availability issues in Salt and Verde rivers (Gregg Garfin PI). **Bonnie Colby**: Walton Family Foundation, 2010-12.

Partners

Connie Woodhouse: We are working on a related project in the lower Colorado River basin with collaborators at the University of Colorado who are funding through the Colorado River District and the State of Colorado.

Future Research

The project end date for Phase III is September 30, 2011. During the late spring and summer of 2011, the University of Arizona team will be wrapping up its research for this Phase. In the meantime, discussions regarding a possible Phase IV have been instigated. To date, two phone conferences have been conducted between UA researchers and Reclamation (Jim Prairie, Hydrologic Engineer and Carly Jerla). This section summarizes the top one or two proposed research projects for Phase IV based on Reclamation needs.

Economics Sub-group

1. The goal of this project is to investigate the range of likely costs of water supply reliability agreements under varying degrees of system shortage in the Upper and Lower Basins. This work is intended to improve understanding of the relationship between water costs and hydrologic and system conditions, and to enhance the ability to predict costs for voluntary arrangements designed to enhance supply reliability.

2. The goal of this project is to develop principles for designing and implementing voluntary programs that can be applied to climate adaptation for Reclamation and its stakeholders throughout in the Basin. Agricultural, industrial and municipal water users served by Reclamation projects in the Upper and Lower Basins anticipate that voluntary and temporary leasing and banking of water provided by Reclamation and stored in Reclamation facilities will be a key strategy for adapting to increased supply variability under climate change. Research focused on improving program cost effectiveness, particularly in refining the provisions of system conservation agreements with districts and their monitoring and enforcement, should enhance adaptive capacity throughout the basin.

Paleohydrology Sub-group

1. The goal of this project is to identify potential climatic drivers of spatial patterns of precipitation across the basin within the context of the western US. In particular, prior work suggests the importance of the Aleutian low in concert with a center of high pressure over western North America as control on drought. The generation of an index reflecting these conditions could test the relationship with upper CRB drought. If successful, the index could be reconstructed with tree-ring data to provide a long-term context for variations in this index and associated droughts.

2. The goal of this project is to provide a measure of model validation and assessment of projected future streamflow conditions in the Colorado River Basin. In collaboration with the modelling groups, we will compare the statistical and spectral features of the output from downscaled GCM models with those in the long-term reconstructions of streamflow for the CRB. We will focus on the frequency, intensity and duration of droughts.

Hydrology Sub-group

1. The goal of this project is to compare statistical and dynamical downscaled climate projections from two climate models and use the VIC hydrologic model for the Lower Colorado River basin to assess changes in streamflow characteristics in both space and time across the basin. We are also seeking co-

funding through Water Sustainability Program at UA to develop more physically-based bias-correction and temporal disaggregation strategies to correct current limitations of statistically downscaled climate forcing to the hydrologic model.

2. The goal of this project is to translate our improved seasonal climatic forecast skill (see annual report of this team) to water availability. At times, future climate may not even be very important as terrestrial water storage (TWS) can dominate the streamflow response of a basin if the antecedent conditions contain a large amount of snow water equivalent, soil moisture or baseflow. Therefore, the water availability forecasts also need to account for TWS estimated using different methods. The Gravity Recovery and Climate Experiment (GRACE), the Variable Infiltration Capacity (VIC) model driven with near real-time observations and the coupled atmosphere-terrestrial water balance method using NARR real time reanalysis data are all promising tools to obtain both surface and subsurface antecedent conditions that affect TWS. We believe that providing these essential initial conditions along with slightly improved probabilistic seasonal climatic forecasts will lead to more reliable estimates of future water availability. It is anticipated that this work will be submitted for publication sometime in the 2011-2012 academic year.

Atmospheric sciences Sub-group

1. The goal of this project is to characterize future climatology and variability as it pertains to Colorado River streamflow. First, we will perform continuous-time WRF-downscaling for the HadGEM2-ES and the MPI, from the IPCC-AR5 archive over a region to include the Colorado River Basin. These new simulations will allow us to compare AR4 (HadCM3 and MPI_Echam5) and AR5 forcing and give us a larger ensemble for determining the uncertainty of our results. And second, we will analyze the data from these and our two previous downscaling efforts (HadCM3 and MPI_Echam5). In our analysis, we will examine future climatology and variability, as well as decadal variability of ENSO, PDO and NAO as it relates to the Colorado River Basin. We will also conduct an in-depth investigation of intense precipitation events for the Colorado River Basin, including the how they are impacted by the interaction of natural decadal variability and climate change. And lastly, we seek to characterize changes in snow/precipitation for mountainous regions in the Colorado River Basin.

Science communication Sub-group

1. This project aims to enhance capacity for the use of climate change science in decision making, through exchange of knowledge between water managers and scientists, in a series of workshops focused on needs articulated by Arizona water managers. Goals include: 1) improve relationships between scientists and water managers; 2) enhance capacity for the use of climate change science in decision-making; and 3) enhance exchange of knowledge and information flows between management, operations, and research sectors. Projecting future climate parameters and their impacts on water resources requires explanation of a complex climate system and models that may seem like black boxes to non-modelers, as well as conveying information on the multiple forms of uncertainty that factor into planning for the future. For instance, previous workshops have identified as a key topic for future discussion, the reliability and usefulness of projections of future climate and hydrologic extremes for central Arizona water resource and flood control managers.

Appendix A

Weather, Climate, and Environmental Water Transactions

LANA JONES AND BONNIE COLBY

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(Manuscript received 22 June 2009, in final form 5 May 2010)

ABSTRACT

Obtaining water for environmental purposes, such as habitat restoration or water quality improvements, has become an important objective in many parts of the world. Such water acquisitions are likely to become more challenging as regional water demand and supply patterns are altered by climate change. In regions where water supplies are already fully claimed, voluntary negotiated transactions have become a key means to obtain water for the environment. The cost of acquiring water in such transactions is hypothesized to vary with regional weather and climate conditions due to both the actual effects of temperature and precipitation on water supply and demand and the perceptions water users may hold about these effects.

This article develops econometric models to examine the effect of temperature and precipitation on water lease prices in four U.S. states located in the desert southwest. Water leases for environmental and non-environmental purposes are contrasted to understand the differing nature of these lease markets and the role of weather and climate variables. The authors' analysis finds that temperature, precipitation, regional income, and population changes are variables that have differing effects in the two lease markets. Overall, analysis of over 20 yr of data shows the need to consider climate and weather factors given the growing importance of water leases as a tool to secure water for the environment.

1. Introduction

Voluntary water transactions occur in many parts of the world and serve an important function in providing water for new uses through a market process. This paper examines the influence of various factors, including weather and climate variables, on transaction prices for two categories of water transactions. In the first category are transactions motivated by a need to acquire water for instream flows, habitat restoration, water quality improvements, and species recovery programs. Such environmental transactions used to be quite rare but now are an important strategy for preserving and restoring water-dependent habitat and species. The second category, in contrast, includes transactions for urban, agricultural, and industrial purposes.

A better understanding of the differing role that regional precipitation and temperature patterns play in various types of water transactions is important to those public agencies, nongovernmental organizations (NGOs), businesses, and citizen groups concerned with preserving water-dependent amenities. We add to a relatively thin literature that has empirically explored the role of climate variables in water transaction prices. In considering precipitation and temperature separately, we depart from previous studies to examine their different effects on water prices. Negotiated prices arise from buyers' and sellers' expectations of future water availability and perceptions of climate conditions that may affect water supply and demand. We include climate variables in our model that people can observe and bear in mind as they consider participating in a water lease.

The increase over the past two decades in water leases for environmental purposes now provides adequate data for a rigorous investigation into the factors affecting prices of water acquired. We develop econometric models of water leases for both environmental and nonenvironmental purposes in the western United States to gauge the effect of local population growth, income, drought, temperature, and development pressure on lease prices. We find both systematic similarities and differences in the price determinants of environmental and nonenvironmental water leases in the four western states of Arizona (AZ), California (CA), New Mexico (NM),

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and Utah (UT). Exploration of factors affecting prices of water purchased for environmental amenities is of practical importance to the many public agencies and NGOs involved in water acquisitions in support of environmental objectives. Moreover, examination of lease prices can complement nonmarket valuation techniques by revealing what factors influence the value of nonmarket amenities such as water-dependent habitat and stream flow levels (Loomis et al. 2003).

Participants in water leasing encompass a wide array of interests. Municipalities, agriculture and industry have been active as both water lessors and lessees for many decades. They use lease arrangements to improve supply reliability and fill in gaps in their permanent water supplies. Public agencies with a mandate to preserve species and habitat, along with environmental NGOs, are the principal lessees in environmental transactions. The lessors include farmers, irrigation districts, and cities that hold a water entitlement they are temporarily willing to refrain from using in exchange for a lease payment. Typical leases last one season or year but sometimes extend for multiple years. The institutional and legal framework is important in water leases, because applicable public policies must provide for temporary transfers of water entitlements. All of the states covered in the model developed here allow for water leasing. In our data, lease duration for both environmental and nonenvironmental leases varies between a few months and 50 yr, with an average duration of 2 yr. Mean price per acre foot over the study period is $80 for the environmental leases and $101 for the nonenvironmental leases, with both types of leases having a similar mean quantity of about 22 000 acre feet (more detailed statistical comparisons between the two types of leases are provided in Tables 1, 3, and 4).

2. Literature review: Statistical analyses of water transactions data

A number of researchers have applied statistical methods to examine various aspects of water transactions in the western United States. Here, we briefly review literature that has included a quantitative analysis of transaction data and characteristics.

Brewer et al. (2007) summarize and describe lease and sale prices and water volumes traded by sector. They use *Water Strategist* data from 1987 to 2005 for 12 western states with a focus on trades from agriculture-to-agriculture, agriculture-to-urban, and urban-to-urban uses. In contrast to other studies reviewed here, Brewer et al. did not develop a regression model to examine relationships among variables related to water transactions. Their focus was on describing the types of transactions that had been observed and price and quantity trends over time. Their examination of transaction information found that most water transfers were agriculture to urban; prices were higher for agriculture-to-urban transfers than for agriculture-to-agriculture transfers; and the number of short-term leases is not increasing but sales and multiyear leases are increasing.

Brown's (2006) analysis of western water markets used 14 yr (1990–2003) of water sale and lease data from the *Water Strategist*. Brown used regression models to examine water sale and lease prices separately to determine what factors influence price. For leases, higher prices occurred for drier climates, larger populations, and municipal and environmental use compared to agricultural use. For sales, more recent transactions, smaller quantities, smaller population, and surface water versus groundwater transfers were associated with higher prices. Sale price was highest for municipal use, followed by irrigation use and then environmental use. A drier climate was not a significant determinant of sale price. Lease price was not affected by quantity, suggesting that transaction costs do not influence leases as much as sales (Brown 2006).

Brown used the Palmer Drought Severity Index (PDSI), an index using both precipitation and temperature data, to test the effect of drought on prices. We use separate measures—the standard precipitation index (SPI) and mean monthly temperature—to test for their separate effects on price. Brown's analysis was an important early statistical exploration of water transaction data. However, the models were not tested for endogeneity, which our analysis finds to be a common problem in water transaction data and one that needs to be addressed and corrected to obtain valid statistical results. Further, given that climate change is expected to have significant and potentially dissimilar effects on temperature and precipitation, it is useful to examine the effect of these two climate variables separately.

Brookshire et al. (2004) look at price history in three specialty water markets to examine past determinants of price as well as to provide a means to predict water right prices. They compare the prices, administration and infrastructure, and legal structures of three distinct water markets in subregions of Arizona, Colorado, and New Mexico. They investigate the role of population change, per capita income, type of buyer, and climate (using the PDSI) on water right prices. The two-stage least squares approach is used to estimate a demand equation, with price estimated in the first stage. From their first-stage equation, they conclude that prices are higher in the Middle Rio Grande region of New Mexico and the Front Range of Colorado compared to Arizona and attribute this difference to market maturity in New Mexico and Colorado. Government buyers pay less than agricultural buyers, but no statistically significant difference was found between prices paid by municipal buyers and agricultural buyers. The drought measure, PDSI, shows that prices are lower during wetter periods. Population has no significant effect on price, but higher per capita income is associated with higher prices. The second-stage equation is estimated for quantity as a function of price, value of agriculture, and land prices (all logged). They find that demand is price elastic, quantity transacted goes down as the value of agriculture rises, and higher quantities are related to higher agricultural land value.

Brookshire et al.'s contribution was to contrast three specific geographic markets rather than to consider differing effects of variables on types of transactions across a broad portion of the west. Environmental buyers are not included in their model nor are transactions located outside the specific subregions they studied in Arizona, New Mexico, and Colorado. We test for the effect of mean monthly temperature and standard precipitation index on price instead of using the PDSI to further understanding about these two critical climate variables.

Loomis et al. (2003) document water market transactions for environmental purposes in the western United States. They argue that water continues to be used off river to irrigate low-value crops when that water would be more valuable for instream purposes and that environmental uses of water are sometimes ignored because they are hard to place a dollar value on. They examine the value of water using average annual quantity and price for selected water transactions over the period 1995–99. They find that lease values were similar to nonmarket values that have been estimated for instream flows in other studies. The most common use for both leases and sales was instream flows. Other common uses were recreation, threatened or endangered species, waterfowl, and fisheries. Loomis et al. conclude that environmental values now exceed agricultural values of water in some instances because government agencies and nonprofit organizations have been able to purchase water from farmers. Loomis et al.'s (2003) primary contribution is to demonstrate that values obtained from market transactions for water rights provide useful information about the value of water-related amenities.

Bjornlund and Rossini (2005) aim to empirically explain the factors affecting price and quantity of water allocations traded using mean monthly water prices in the Goulburn Murray Irrigation District and monthly volumes traded from Goulburn Murray Water in Victoria, Australia. Price and volume were studied using correlation analysis, regression analysis (both inflation adjusted), and time series analysis. Price was regressed on seasonal water allocation level; the level of monthly evaporation measured at Kyabram, Victoria; interest rate; and cattle, wool, and wheat prices. Volume was regressed on monthly evaporation and rainfall at Kyabram, the accumulated deficit between evaporation and rainfall, lease prices, and a dummy variable for trades occurring during summer months, using first differences. Results showed that evaporation affected current trading volumes and that trading increased as the deficit between rainfall and evaporation increased. In this study, commodity prices were less important than expected and had inconsistent effects on prices. The most important determinants of water price and volume were allocation, rain, and evaporation. High-value farmers pushed prices up during drought by buying water to protect their investments. The authors conclude that the results show that irrigators need water markets to manage variable water supply. High-value users will increasingly need to buy or lease water, and low-value users will either sell their rights or lease them in dry years and use them only in normal or wet years. Urban water authorities should also plan ahead (using dry-year options) for periods of dryness instead of relying on lease markets to avoid drought-induced price instability. This research is valuable in extending the type of variables used to model transaction prices, including crop prices, interest rates, and water supply deficits. They included climate factors in their analysis using measures of monthly evaporation and rainfall. In contrast, we test for the effects of precipitation and temperature separately, using the standard precipitation index and mean monthly temperature.

The econometric model developed here differs in important respects from the handful of previously published statistical models of water transaction data. The model presented draws upon 20 yr of transaction data for four U.S. states, with a specific focus on the role of temporary water transfers (leases) and on contrasting the influence of model variables on prices negotiated in environmental versus other types of transactions. The econometric models employed were tested for (and corrected for) common statistical problems encountered in using transaction data: endogeneity between observed prices and quantities traded; heteroskedasticity; and collinearity. The rigorous statistical analysis reported here adds to the collective understanding of the emerging market for water leases dedicated to environmental purposes, particularly the influence of weather and climate factors. Water leases to maintain and restore environmental amenities are likely to be an important adaptation strategy to the changing climate of the United States.

3. Data and model

The water lease data used in the analysis comes primarily from the *Water Strategist* for the years 1987–2007.[1] This information (accessible through paid subscription) is supplemented by the authors' research files on leases. A summary of leases by state and type is in Table 1.[2] Leases are measured in acre feet per year and generally last only a few years but can span decades. Transactions are not necessarily representative of the water market as a whole. The *Water Strategist* does not claim to report all water transactions, but any selection bias is expected to be consistent across states (Howitt and Hansen 2005).

Transactions are reported by month and year. The date they are reported may be several months after the date the transaction was negotiated. Lagged independent variables are employed to account for the fact that the time period in which the negotiations occurred preceded the transaction report date and the negotiation time period is not available.

It is useful to examine trends in the data used in the models developed here. Environmental water leases have become more common over the past 20 yr compared to nonenvironmental water leases, as shown in Fig. 1 (Shupe and Folk-Williams 1987; Smith and Vaughan 1990; Smith 2002). The trend in prices over time also diverges for environmental and nonenvironmental leases. Figure 2 shows the average prices each year for both types of leases in 2007 dollars. Environmental lease prices appear to have an upward price trend, whereas nonenvironmental leases have a less pronounced downward price trend.

TABLE 1. Transaction summary: Summary statistics for environmental and nonenvironmental water leases in AZ, CA, NM, and UT from 1987 to 2007. Quantity is in acre feet, and prices are in 2007 dollars per acre foot.

	AZ	CA	NM	UT	Tot
		Environmental leases			
n	13	112	54	3	182
Min quantity	75	120	16	1900	16
Mean quantity	10 691	30 959	6967	4433	21 956
Max quantity	89 583	200 000	70 000	9500	200 000
Min price	44	8	8	30	8
Mean price	52	96	54	51	80
Max price	77	384	147	89	384
		Nonenvironmental leases			
n	57	576	25	18	676
Min quantity	8	2	49	74	2
Mean quantity	133 315	12 760	7055	6773	22 554
Max quantity	1 200 000	500 000	44 760	15 924	1 200 000
Min price	8	6	25	7	6
Mean price	97	105	72	29	101
Max price	787	1290	114	188	1290

We estimate a demand model for prices observed in environmental water leases and for nonenvironmental water leases, as a basis for comparison.[3] Similar demand models have been used in the literature on more aggregated sets of transactions data (Brookshire et al. 2004). The demand equation is solved for price, with leases modeled separately for the environmental and nonenvironmental water markets using a semilog functional form.[4]

Two-stage least squares regression was used to estimate lease prices. In two-stage least squares, two regressions are estimated in a situation where one ordinary least squares regression would lead to inconsistent estimators. Two-stage least squares allows for consistent estimation when endogeneity is a problem. Endogeneity may be a problem when using quantity as a regressor for price if these values are simultaneously determined. The regression form of the Hausman test (Wooldridge 2002) was performed to check for endogeneity with the result

[1] The *Water Strategist* (formerly known as the *Water Market Update* and *Water Intelligence Monthly)* is a monthly publication detailing water sales and leases in the western United States as well as trends in water policies, laws, and legal actions. The *Water Strategist* provides varying degrees of detail on the buyer, seller, price, quantity, and other characteristics of water transactions.

[2] Some transactions were removed from the dataset. Transactions were removed if the price was undisclosed (e.g., sold together with land), if the information provided was too ambiguous to extract price or quantity, or if the price was less than \$5.00 (acre foot)$^{-1}$. Transactions under \$5.00 (acre foot)$^{-1}$ were removed because they are unlikely to represent true market transactions; they often involved transactions between family members. Transactions were also removed if they were for reclaimed water. Reclaimed water is inherently different from other surface or groundwater: it has restricted uses because of political, technological, and environmental constraints. Leases were reclassified as sales if they exceeded 50 yr in length.

[3] A Chow test was used to investigate whether environmental and nonenvironmental leases should be modeled separately. The null hypothesis that the coefficients were the same for the two models was rejected indicating that they should be modeled separately.

[4] We chose a semilog form for a number of reasons. First, outliers in price led to a poorly fitting model and nonnormally distributed errors. Taking the natural log improved the model's fit and returned errors that more closely approximated a normal distribution. Second, we suspected there was a nonlinear relationship between price and explanatory variables like temperature, precipitation, and income. Third, past studies have used this form and found it to model price behavior well.

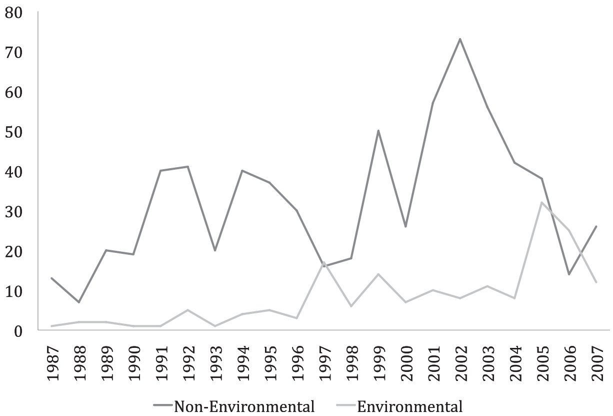

FIG. 1. Number of leases per year: The number of temporary water transfers for environmental and nonenvironmental water uses, 1987–2007, in AZ, CA, NM, and UT.

FIG. 2. Mean annual lease prices (2007 dollars): Annual-mean prices for temporary water transfers for environmental and nonenvironmental uses, 1987–2007, in AZ, CA, NM, and UT.

that the null hypothesis of exogenous quantity was rejected in the nonenvironmental lease model. Lease price and quantity are suspected to be endogenous because no prevailing water price exists and prices and quantities are simultaneously negotiated. Although the test failed to reject exogeneity of quantity in the environmental lease model, two-stage least squares was still used for three reasons: no compelling argument exists for independent determination of prices and quantities in environmental lease transactions given endogeneity in the nonenvironmental leases in the same geographic area; the instruments are weaker in the environmental model so the endogeneity test results may not be reliable; and comparability with the nonenvironmental lease model is maintained. The results of the endogeneity and instrument tests are in the appendix.

Two-stage least squares regression solves the endogeneity problem by estimating quantity in a first-stage ordinary least squares regression. This estimated value for quantity is then used in the second-stage ordinary least squares regression of price. The estimated value of quantity is not simultaneously determined with price, so the consistency of estimators is no longer a problem. The two-stage least squares estimator is less efficient than the ordinary least squares estimator; however, if endogeneity is present, the ordinary least squares estimator will be inconsistent (Greene 2003). As suggested by Thurman (1986), the exogeneity of price was also tested in quantity-dependent models for comparison. In the environmental lease model, the exogeneity of price was rejected, supporting the idea that price and quantity are endogenous. Heteroskedasticity was suspected so the endogeneity test was carried out using robust standard errors. The inferences did not change when robust standard errors were used.

Heteroskedasticity may be a problem, particularly because the models include multiple western states. Examination of the errors revealed no apparent patterns. We used a Bruesch–Pagan–Godfrey test (Johnston and Dinardo 1996) modified to allow for endogeneity to test for heteroskedasticity. Homoskedasticity was rejected and heteroskedasticity was corrected using robust standard errors.

Collinearity was investigated using variance inflation factors and condition indexes. Some degree of collinearity was detected in all models. The collinearity stems from the inclusion of state dummies and variables measuring income or land value. Despite some collinearity, we chose to leave these variables in the model as essential components in understanding transaction patterns. State dummies help account for differences between states, such as legal or administrative differences. Income is expected to be an important component in both demand and prices for environmental and nonenvironmental water. Collinearity was reduced by using a ratio of agricultural real estate value to agricultural income instead of those variables alone or separately. Per capita income remains untransformed in the model and still leads to some collinearity. Significance of variables, their magnitudes, and their signs are not significantly affected by the remaining collinearity.[5]

Four desert southwest states are included in this analysis: Arizona, California, New Mexico, and Utah. No environmental leases were reported for Nevada, so it is not included in the models.

[5] Dropping the per capita income variable does not cause significant changes in these values.

TABLE 2. Summary of variables: Summary of variables used in regression analysis of environmental and nonenvironmental water lease prices in AZ, CA, NM, and UT, 1987–2007.

Name	Description	Expected sign
lnP07	Natural log of real price (2007 dollars)	
Q	Quantity in acre feet	−
Temp3	Temperature lagged 3 months by climate division	+
L3SP06	SPI 6 lagged 3 months by climate division	−
Income	Quarterly real per capita income by state	+
LandInc	Ratio of agricultural real estate value to net income per acre	+
DivPop	Yearly population by climate division	+
NumTrans	The number of transactions per climate division per year	+/−
Yrs	Length of lease	+/−
Dummy variables (equal to 1 for):		
Pub	State or Bureau of Reclamation project water	−
Mand*	New use for threatened and endangered species or water quality	
Env	New use is general environment or recreation	−
Multi	New use for both environmental and nonenvironmental purposes	+
Ag*	New use is agricultural	
Muni	New use is municipal, domestic, or municipal industrial	+
Dev	New use for development	+
Ind	New use is power plant or mining	+
Noncu	New use is storage, interstate compact, or tribal settlement	−
Other	New use is unknown or multiple nonenvironmental uses	+/−
Transaction location dummies: AZ, CA,* NM, UT		
Instrumental variables		
Split	=1 if *Water Strategist* entry was split into multiple observations	−
L3SP24	SPI 24 lagged 3 months by climate division	−
L2Income	Real per capita income by state lagged two quarters	+

* Baseline dummy.

4. Variables

The variables used in the two-stage least squares regressions of water lease prices are summarized briefly in Table 2.

a. *lnP07*

The natural log of the price per acre foot of water leased in 2007 dollars: Price was deflated using the consumer price index for 2007 from the Bureau of Labor Statistics Web site (BLS 2007). Price is the dependent variable.

b. *Q*

The quantity purchased in acre feet: The sign of the quantity coefficient is expected to be negative, indicating a downward-sloping demand curve. Quantity is estimated in the first stage of the two-stage least squares model. The predicted values of quantity from the first stage are then used in place of actual quantity in the second stage to control for endogeneity.

c. *Temp3*

The mean monthly temperature in the climate division where the water was acquired: To reflect temperature conditions prevalent in the time frame the transaction was being negotiated, mean monthly temperature is lagged 3 months from the date the transaction was reported to account for the time needed to complete a transaction and for it to be reported. Temperature data were obtained from the National Climatic Data Center Web site (NCDC 2007). The sign of the temperature coefficient is expected to be positive; higher temperatures are expected to be associated with higher prices. The monthly mean temperature was used instead of a constructed temperature index, similar to the SPI described later, because the accumulated effect of abnormal temperatures are not analogous in their effect on water supply and demand to the effect of cumulative abnormal precipitation.

d. *L3SP06*

The SPI measures drought in terms of standard deviations from the mean. These deviations are calculated using accumulated precipitation over the past months (e.g., last 6 or 12 for SPI06 and SPI12) compared to the long-term precipitation mean in the same climate division. The index will be negative if precipitation has been below normal and positive if it has been above normal. More extreme values indicate more extreme conditions. The shorter index measures recent conditions, whereas the longer index gives an indication of more chronic conditions (WRRC 2008). The variable is lagged 3 months, allowing for time to complete a transaction and possible delay in reporting by the *Water Strategist*. SPI data were obtained from the National Climatic Data Center Web site (NCDC 2007). The sign of the SPI coefficient is expected to be negative. As conditions become wetter, the value of the SPI becomes larger and the price is expected to decrease.

L3SP06 is the only variable measured in deviations from the mean. This measure was chosen because deviations from normal precipitation are expected to influence water prices more than the absolute monthly level of precipitation. This is the case because of the cumulative effects of precipitation on regional water supply and demand. If precipitation is low for multiple months, lease prices are expected to be higher. If precipitation recovers for 1 month but is still below the 6-month norm, we expect prices to continue to be higher.

A key contribution of this paper is to add to empirical exploration of the role of climate variables in differing types of water transactions. In considering precipitation and temperature separately, we take a departure from previous studies. Brown (2006) uses PDSI, a drought measure that incorporates temperature and precipitation. He found that higher lease prices were associated with more severe drought. Bjornlund and Rossini (2005) examine the effects of monthly evaporation on water prices. Seager et al. (2007) use precipitation minus evapotranspiration in their models; however, they do not model water prices.

Testing precipitation and temperature separately allows us to see if each of these climate variables has a different effect on water prices. Water prices are based not only on climatic conditions but also on people's perceptions of those conditions and their implications. Lease prices are at least partially the result of buyers' and sellers' expectations of future water availability and costs, as well as perceptions of climate conditions. Lessees may be willing to pay more for water after there has been a prolonged dry period, with a noticeable effect on water supplies, and lessors may hold out for a higher price. The effects of hotter-than-normal temperatures are typically less noticeable in the time frame in which water leases are negotiated than the effects of low precipitation. Nevertheless, future precipitation and temperature patterns are projected to vary significantly from past patterns given climate change, so it is useful to examine each of these climate variables. Given the importance of perceptions in affecting prices, it is important to use climate variables that people can observe and are likely to be aware of as they consider participating in a water lease.

e. *Income*

Income is the quarterly per capita income at the state level lagged one quarter. Income data comes from the Bureau of Economic Analysis Web site (BEA 2007). Income at the climate division instead of state level would be preferable but was not available dating back to 1987. The sign of the income coefficient is expected to be positive. Environmental, municipal, and agricultural water are all expected to be normal goods.

f. *LandInc*

The average real estate value of agricultural land per acre divided by the average agricultural net income per acre: Both are at the state level and in 2007 dollars. Real estate value and net farm income come from the Economic Research Service Web site (ERS 2008). This variable measures the value of land compared to the value it produces. States with more development pressure are expected to have a higher land value to income ratio. The sign of the LandInc coefficient is expected to be positive, because previous studies show municipal users are willing to pay more than agricultural users.

g. *DivPop*

The population by year and climate division lagged 2 yr in tens of thousands. The climate division population was calculated by summing populations of counties located within the same climate division. A climate division and county map (CPC 2008) were consulted if a county spanned more than one climate division and the county was added to the division where the majority of its area lay. Populations are from the Census Bureau Web site (Census 2008) and were lagged because county population was only available up to 2005. This was acceptable, because population changes may take some time to influence water prices. We expect climate divisions with growing populations to have plenty of supplies available to meet current population needs at any given time. The sign of the DivPop coefficient is expected to be positive; higher prices are expected to be associated with larger populations.

h. *NumTrans*

The total number of transactions reported per climate division per year, including sales and leases for all purposes. A priori, we do not have an unambiguous hypothesis regarding the sign of the NumTrans coefficient. As the number of transactions increases, more parties may become comfortable participating in transactions and there may be increased competition for available water and upward pressure on price. However, the sign may be negative if a more active market operates more smoothly and in a manner that reduces overall participant transaction costs.

i. Yrs

The length of a lease in years, ranging from less than one to 50: The expected sign of the Yrs coefficient is ambiguous, because reasonable arguments can be made for either a positive or negative coefficient. Some prior studies have found economies of scale with lower per unit prices in larger water transactions (Colby 1990), and a similar reasoning could apply to the larger cumulative volumes that are transferred via longer leases. On the other hand, in the presence of nontrivial transaction costs, buyers may be willing to pay more per unit for a longer lease because they will not have to engage in multiple transactions to secure water for the duration of their expected leasing need.

j. Pub

A dummy variable that equals one if the water is administered by a state or government agency instead of a private water user: Examples are the State Water Project in California and the Central Arizona Project. The sign of the Pub coefficient is expected to be negative, because public project water can be perceived as more susceptible to reallocation if endangered species or other public interest issues arise and thus less secure than leasing private water rights (Howitt and Hansen 2005).

k. Mand

A dummy variable that equals one if the water was purchased for uses mandated by law, threatened or endangered species, or water quality improvement: This is the baseline variable in the environmental water models.

l. Env

A dummy variable that equals one if the water was purchased for general environmental purposes (e.g., instream flows, recreation, and open space). These transactions were not mandated by law to protect endangered species or water quality. They represent voluntary transactions for environmental water uses. The sign of the coefficient is expected to be negative, and general environmental uses are expected to represent demand that is more own-price elastic than mandatory environmental uses.

m. Multi

A dummy variable that equals one if the water was purchased for uses that include environmental and nonenvironmental purposes: For example, a city purchasing water for municipal and open space use would be classified as Multi. The sign of the coefficient is expected to be positive, because agricultural and municipal users are expected to be willing to pay more for water than purely environmental water users.

n. Ag

A dummy variable that equals one if the water was purchased for agricultural use: This is the baseline variable in the nonenvironmental models.

o. Muni

A dummy variable that equals one if the water was purchased for municipal use: Municipal uses include general domestic, light industrial, and golf course or landscaping. The sign of the coefficient is expected to be positive; municipal buyers are expected to be willing to pay more than agricultural buyers.

p. Dev

A dummy variable that equals one if the water was purchased for new development: Although development could also generally be classified as municipal use, the Dev variable was created to capture the differing effects of new development compared to other municipal uses. Muni and Dev are mutually exclusive categories. The sign of the coefficient is expected to be positive; developers are expected to be willing to pay more than agricultural buyers.

q. Ind

A dummy variable that equals one if the water was purchased for heavy industrial uses (power plants or mining). The sign of the coefficient is expected to be positive; heavy industrial users are expected to be willing to pay more than agricultural users.

r. Noncu

A dummy variable that equals one if the water was purchased for a nonconsumptive but nonenvironmental use including storage that is not obviously purchased for another use, tribal settlements, and interstate compacts. The sign of the coefficient is expected to be negative; nonconsumptive users are expected to be willing to pay less than agricultural users.

s. Other

A dummy variable that equals one if the water was purchased for either unknown or multiple nonenvironmental uses: Transactions that could not be classified into one of the earlier categories (either because the new use of the water was not specified in the transaction data or the water was purchased for multiple nonenvironmental uses) are categorized as Other. For example, water purchased for both agricultural and industrial uses is classified as Other, not agricultural or industrial. We have no expectation about the sign of this coefficient, but it is necessary so that each transaction has a use designation that can be contrasted against the baseline Ag use category in the nonenvironmental model.

t. Location dummies

Dummy variables for each of the states, AZ, CA, NM, and UT: CA is taken as the baseline. The signs of the AZ, NM, and UT coefficients are expected to be negative. California users are expected to pay more because of the already full use of available water in the state. Political demographics and legal structures in the state may also contribute to higher prices.

Three instrumental variables are used in addition to the earlier variables to estimate quantity in the first stage of the lease models. The dependant variable in the first stage is actual quantity. The instruments were chosen based on their correlation with the quantity transacted and absence of correlation with the error in the price equation.

u. Instrumental variables

1) SPLIT

A dummy variable that equals one if the original entry in the *Water Strategist* provided information about more than one transaction with enough detail for it to be split into multiple observations. The sign of the coefficient is expected to be negative; observations from split entries will have smaller quantities than observations representing multiple transactions. The relationship with quantity makes this a useful instrumental variable.

2) L3SP24

An extra 24-month SPI term is used to capture the effects of long-term conditions on the amount of water demanded. The sign of the coefficient is expected to be negative; wetter conditions (more positive SPI) will lead to less demand in the water market.

3) L2INCOME

An extra lagged income term: Quantity is expected to increase as income increases. The expected sign of the coefficient is positive.

TABLE 3. Summary statistics environmental leases: Summary statistics of variables used in environmental water lease regression for transactions in AZ, CA, NM, and UT, 1987–2007; $n = 182$.

Variable	Mean	Std dev	Min	Max
lnp07	4.12	0.79	2.08	5.95
Q	21 956	32 076	16	200 000
Temp3	64.82	12.96	36.10	91.50
L3SP06	0.38	1.07	−2.44	2.23
Income	33 420	4823	23 077	40 868
LandInc	18.90	10.94	8.75	112.23
DivPop	256	197	10	1605
NumTrans	11.69	7.22	1	28
Yrs	1.80	3.71	1	25
Pub	0.47	0.50	0	1
Mand	0.27	0.45	0	1
Env	0.71	0.46	0	1
Multi	0.02	0.13	0	1
AZ	0.07	0.26	0	1
CA	0.62	0.49	0	1
NM	0.30	0.46	0	1
UT	0.02	0.13	0	1
Split	0.70	0.46	0	1
L3SP24	0.39	0.90	−1.71	1.90
L2Income	33 158	4840	22 561	40 366

5. Empirical results

Leases may be preferred for environmental purposes when buyers and sellers are unfamiliar with the market, or with the effects of moving water on the environment and the community (Loomis et al. 2003). Most environmental leases over the decades examined occurred in California, but New Mexico also had a large number of transactions. For summary statistics, see Table 3. In both states, the Bureau of Reclamation and state agencies are frequent purchasers of environmental water. Environmental leases in California are used for a variety of purposes, including salmon migration, waterfowl habitat, riparian areas, and delta restoration. Most New Mexico leases are related to the Rio Grande and the endangered silvery minnow.

The majority of nonenvironmental leases also take place in California. Leases are frequently used in California because of the environmental and third-party impacts associated with sales (Howitt and Hanak 2005). The largest leased quantities are transactions for Central Arizona Project water. Summary statistics for nonenvironmental leases are in Table 4.

Both models are in a semilog functional form; nondummy variable coefficients represent the percent change in price for a unit increase in the variable. For dummy variable coefficients, the percent change in price is given by $e^B - 1$ (Kennedy 2003). Models are estimated using two-stage least squares. The results from the first stage are in the appendix. The R^2 for the models fall between those reported by similar studies; the environmental model has an adjusted R^2 of 0.319, and the nonenvironmental model has an adjusted R^2 of 0.453. Brown (2006) reported an adjusted R^2 of 0.21 for leases.

TABLE 4. Summary statistics nonenvironmental leases: Summary statistics of variables used in nonenvironmental water lease regression for transactions in AZ, CA, NM, and UT, 1987–2007; $n = 676$.

Variable	Mean	Std dev	Min	Max
lnp07	3.97	1.25	1.70	7.16
Q	22 554	91 841	2	1 200 000
Temp3	62.19	11.95	22.30	91.50
L3SP06	−0.34	1.09	−3.09	2.39
Income	34 406	3851	22 398	40 868
LandInc	16.73	8.23	8.75	58.83
DivPop	585	516	14	1705
NumTrans	15.24	10.87	1	42
Yrs	1.98	4.49	0	50
Pub	0.43	0.50	0	1
Ag	0.28	0.45	0	1
Muni	0.45	0.50	0	1
Dev	0.01	0.09	0	1
Ind	0.01	0.12	0	1
Noncu	0.04	0.21	0	1
Other	0.21	0.40	0	1
AZ	0.08	0.28	0	1
CA	0.85	0.36	0	1
NM	0.04	0.19	0	1
UT	0.03	0.16	0	1
Split	0.79	0.41	0	1
L3SP24	−0.18	1.11	−2.21	2.79
L2Income	34 441	3884	22 920	40 366

Brookshire et al. (2004) reported an adjusted R^2 of 0.734 for their price estimation model, including both sales and leases. Estimation results and marginal effects for both models are presented in Table 5.

a. *Environmental lease results*

Temp3, the mean temperature 3 months before the transaction was reported, is significant in the environmental lease model but has an unexpected sign. In general, we would expect increased temperatures to increase the demand for and price of water transacted. The mean temperature from 3 months before the transaction was reported may not be a precise enough variable to detect an accurate relationship between temperature and prices. If the actual date on which the negotiating parties finalized a transaction was known, a better measure might be constructed. Although the absence of information on the transaction may be a hurdle to analyzing the relationship between climate factors and water price, this analysis used the most comprehensive source available on water transactions.

In the environmental model, the precipitation index L3SP06 is not significant. It may not be significant because demand for environmental water may be more closely related to general, not drought-related, efforts to rehabilitate rivers and habitats. The significance of variables in the environmental lease model may also be affected because of the low number of transactions compared to the nonenvironmental lease model. Environmental leases were uncommon until around 1996.

Income is significant and positive in the environmental model. The marginal effect of income is 0.011%; as state per capita income increases \$1000, environmental water lease prices are predicted to increase 11%. Water for environmental purposes may be viewed as a luxury good, leading to the large positive effect.

The dummy for public water leases is significant. Public water is expected to be less expensive than privately held water, and the marginal effect supports this expectation. Prices are predicted to be 29% lower for public water than for private water for environmental leases.

Water prices for general environmental and multiple uses are significantly more expensive than for mandated environmental uses by 47.1% and 211.9%. Multiple uses may be much more expensive, because municipal or agricultural uses may be included in this use. General environmental uses were expected to have lower prices than mandated environmental uses. The higher price may represent an effort by communities or states to protect a resource or species before it becomes listed to avoid legal fees or penalties.

Arizona and New Mexico are found to have higher environmental lease prices than California. Their marginal effects are 86.2% and 127.9%. We expected prices to be higher in California; however, once its high income and population are controlled for through inclusion of those variables in the model, the coefficients for ''state'' are positive for Arizona and New Mexico compared to California.

b. *Nonenvironmental lease results*

Quantity is significant and positive in the nonenvironmental leases model. The positive relationship between price and quantity is unexpected, although Colby (1990) has shown that larger transactions have lower transaction costs per acre foot.[6] Over time, as water leases become more popular and an efficient market emerges, transaction costs should decrease. The positive sign might indicate that water lease markets are still developing. Quantity was not significant in Brown's (2006) lease model, and Brookshire et al. (2004) did not

[6] As quantity leased increases one acre foot, price increases 0.0009%. Buyers may be willing to pay more on a per acre foot basis for large quantities of water in order to avoid having to negotiate several smaller transactions and incur additional transaction costs. The state approval process, the possibility of opposition to the transfer, and the time required to get transfers negotiated and approved all add to transaction costs. Larger transactions have been shown to have lower per acre foot transaction costs (Colby 1990).

TABLE 5. Estimation results and marginal effects: Estimation results for water lease price regression and marginal effects in AZ, CA, NM, and UT, 1987–2007. Robust standard errors are in parentheses. CA is the excluded state, and Ag and Mand are excluded uses.

Variable	Environmental model	Marginal effects	Nonenvironmental model	Marginal effects
Intercept	−0.1310		6.3258[c]	
	(0.9829)		(0.7149)	
Q	0.000 004	0.0004%	0.000 009[a]	0.0009%
	(0.000 01)		(0.000 005)	
Temp3	−0.0079[a]	−0.79%	0.0036	0.36%
	(0.0047)		(0.0042)	
L3SP06	−0.0118	−1.2%	−0.1212[c]	−12.1%
	(0.0491)		(0.0439)	
Income	0.0001[c]	0.011%	−0.0001[c]	−0.007%
	(0.000 02)		(0.000 02)	
LandInc	0.0155	1.5%	0.0247[a]	2.5%
	(0.0125)		(0.0135)	
DivPop	0.0003	0.03%	0.0003[c]	0.03%
	(0.0005)		(0.0001)	
NumTrans	0.013	1.3%	−0.0116[c]	−1.2%
	(0.0086)		(0.0043)	
Yrs	−0.0087	−0.87%	0.0021	0.21%
	(0.0234)		(0.0119)	
Pub	−0.3418[c]	−29.0%	−1.5761[c]	−79.3%
	(0.1343)		(0.0956)	
Env	0.3859[a]	47.1%		
	(0.2077)			
Multi	1.1377[b]	211.9%		
	(0.4792)			
Muni			0.2366[a]	26.7%
			(0.1292)	
Dev			1.0475[b]	185.1%
			(0.4634)	
Ind			−0.8001	−55.1%
			(0.6541)	
Noncu			0.1516	16.4%
			(0.1814)	
Other			−0.4751[c]	−37.8%
			(0.1654)	
AZ	0.6218[a]	86.2%	−0.7703	−53.7%
	(0.3573)		(0.6631)	
NM	0.8236[c]	127.9%	0.0455	4.7%
	(0.3192)		(0.3908)	
UT	0.2265	25.4%	−1.3637[c]	−74.4%
	(0.8328)		(0.4662)	
	n = 182		n = 676	
	Adj. R^2 = 0.319		Adj. R^2 = 0.453	

[a] .10 significance level.
[b] .05 significance level.
[c] .001 significance level.

estimate the effect of quantity on price. They did estimate the effect of price on quantity and found a significant negative relationship. The effect is trivial in magnitude.

The standard precipitation index variable L3SP06 is significant and negative in this model. As the index increases (indicating wetter conditions) by one standard deviation, price decreases by 12.1%. This result is consistent with our a priori hypothesis and also with Brown (2006), who used the PDSI to measure drought.

Income is significant and negative in the nonenvironmental model. A negative result may indicate that, as the state becomes wealthier, permanent purchases of water rights become more feasible and temporary lease arrangements are not the preferred means for supplying water for nonenvironmental purposes. The ratio of agricultural real estate value to net income per acre is positive and significant. Development pressure may be the cause of a higher agricultural land to income ratio and may also lead to increased water prices. Climate division population is also positively associated with price, with a marginal effect of a 0.03% price increase per 10 000-person increase in population. The number of transactions per year per division is negatively associated with price. The sign is unexpected and may be picking up a supply effect. As more sellers enter the market, competition may decrease prices. No effect on price is detected, depending on the number of years of a lease. Although longer leases represent a more sure supply of water, they do not appear to attract higher prices holding other effects constant.

The dummy for public water leases is significant in this model as well. Prices are predicted to be 79.3% lower for public water than for private water for nonenvironmental leases.

Water prices for municipal, development, and other uses are significantly higher than for agricultural use. Municipal and development uses are predicted to be 26.7% and 185.1% higher. The other use (containing multiple and unknown uses) is predicted to be 37.8% lower.

Utah is the only state estimated to have a significantly different price than California in the nonenvironmental model, with a marginal effect of −74.4%. This result confirms our expectation that lease prices would be higher in California.

6. Discussion of empirical findings

Comparisons of the models for environmental and nonenvironmental water transactions reveal relatively consistent, though not always statistically significant, results. The coefficients have similar signs and magnitudes for quantity and population but differ on income. Income has the expected positive effect on water prices in the environmental model. Income in the nonenvironmental leases model shows a small but negative relationship to price. The effects on price of the new water use were as expected: municipal and development lessors pay more per unit of water leased than do agricultural lessors. Multiple uses are found to pay higher lease prices than water leased solely for environmental purposes. In the environmental lease model, California prices were lower than for the other states. This may reflect the greater activity and experience in that state with leasing water for environmental needs.

Population is statistically significant only for the nonenvironmental transactions. The ratio of agricultural land value to net income per acre (LandInc) variable is statistically significant and positive in the nonenvironmental model. This is consistent with the hypothesis that lease prices increase as pressure to develop agricultural land increases.

Testing the effects of precipitation and temperature returned mixed results across the two models. Temperature is not significant for nonenvironmental transactions and is significant and negative (though with a very small marginal affect on price) for environmental transactions. These results suggest that temperature by itself is not an important variable in determining water lease prices. Abnormal temperature patterns do not produce the same observable effect on water supplies as abnormal precipitation patterns. Water users may recover from a heat spell relatively quickly, but recovery from a prolonged drought could take months or years. (Kenney et al. 2010; Rajagopalan et al. 2009). Drought, measured by the standard precipitation index, is found to have a large statistically significant effect on prices for nonenvironmental leases. The lease market is expected to be sensitive to drought because, during a drought, growers of perennial crops and municipal water suppliers enter the lease market to fill deficiencies in their water supply.

7. Conclusions and policy implications

The empirical findings indicate important differences in the factors that affect water lease prices for environmental and nonenvironmental water leases, with varying implications for parties involved in each type of lease. Drier weather, population growth, and development pressures exert an upward influence on water lease prices for nonenvironmental leases, whereas per capita income significantly affects environmental lease prices. Prices emerging in both types of leases are strongly affected by the intended new use and the state in which the transaction occurs.

A number of policy implications emerge from the research findings. First, the use of water leasing for environmental purposes is increasing and seems to be providing an important means to accommodate water needs for environmental restoration and protection. Federal and state agencies would do well to consider how they can streamline the water leasing process so that it can be more widely used and so that procedural requirements and costs are minimized. Second, cities, agricultural districts, and industries that anticipate needing water to support their needs during dry periods would be prudent to consider negotiating price and other lease terms in advance of actual need, because lease prices for nonenvironmental purposes rise during dry periods. Businesses located in areas that are economically dependent on water-based recreation (and snow-based recreation) would do well to consider making advance arrangements to secure water needed for recreational activities during drought to protect their recreation-based revenues. Periods of economic downturn may

TABLE A1. Environmental leases, first-stage results: Estimation results for quantity in two-stage regression for environmental water lease prices in AZ, CA, NM, and UT, 1987–2007. Actual quantity is the dependent variable.

Variable	Estimate	Std error	t value	Pr > t
Intercept	18 415.81	37 625.22	0.49	0.625
Split	−9078.388	5051.813	−1.8	0.074
L3SP24	−5983.026	3249.808	−1.84	0.067
L2Income	12.823 48	4.418 539	2.9	0.004
Temp3	−65.138 94	192.5585	−0.34	0.736
l3sp06	2185.84	2687.885	0.81	0.417
Income	−12.539 56	4.326 878	−2.9	0.004
LandInc	119.8289	341.5922	0.35	0.726
DivPop	53.854 57	14.330 92	3.76	0.000
NumTrans	−408.1386	337.7249	−1.21	0.229
Pub	−9290.958	4847.464	−1.92	0.057
Yrs	1388.59	591.5773	2.35	0.020
Env	2132.311	6406.007	0.33	0.740
Multi	−25 282.18	17 321.4	−1.46	0.146
AZ	−12 225.21	14 649.56	−0.83	0.405
NM	1008.936	12 512.48	0.08	0.936
UT	−22 831.57	27 675.59	−0.82	0.411
n = 182	Adj. R^2 = .293		F = 5.68 (significant at the .001 level)	

present opportunities for environmental agencies and NGOs to secure affordable leases for habitat, stream flows, and endangered species, if per capita incomes are leveling off or decreasing.

Although water users may prefer a permanent acquisition of water to a lease, water leases have become common and will remain a popular solution to meet interim water needs. Leases, particularly during wet periods, may provide a low-cost source of water that can be banked for dryer periods. Many western states already provide arrangements to encourage leasing and banking water supplies (see, e.g., Clifford et al. 2004). Municipal, industrial, and agricultural users may be able to reduce their water expenses considerably by leasing water when supplies are plentiful and banking that leased water underground and in reservoirs for use during drought.

The southwestern U.S. climate is projected to become increasingly arid and subject to water conflicts, as Seager et al. (2007) conclude after examining several

TABLE A2. Nonenvironmental leases, first-stage results: Estimation results for quantity in two-stage regression for nonenvironmental water lease prices in AZ, CA, NM, and UT, 1987–2007. Actual quantity is the dependent variable.

Variable	Estimate	Std error	t value	Pr > t
Intercept	84 612.06	49 096.95	1.72	0.085
Split	−31 166.92	7639.562	−4.08	0.000
L3SP24	−2393.187	3433.489	−0.7	0.486
L2Income	2.173 065	4.435 292	0.49	0.624
Temp3	−362.83	301.0833	−1.21	0.229
L3SP06	−130.2819	3306.766	−0.04	0.969
Income	−2.469 846	4.600 668	−0.54	0.592
LandInc	−2440.296	604.2189	−4.04	0.000
DivPop	21.526 61	7.161 349	3.01	0.003
NumTrans	40.334 61	329.9494	0.12	0.903
Pub	12 238.61	6786.728	1.8	0.072
Yrs	782.9301	670.0782	1.17	0.243
Muni	−13 442.34	7798.499	−1.72	0.085
Dev	−90 258.7	33 776.25	−2.67	0.008
Ind	−103 133.2	26 711.36	−3.86	0.000
Noncu	3012.981	15 105.28	0.2	0.842
Other	29 892.58	9533.24	3.14	0.002
AZ	164 937.6	23 103.07	7.14	0.000
NM	21 676.13	25 845.21	0.84	0.402
UT	42 610.03	30 873.37	1.38	0.168
n = 676	Adj. R^2 = 0.208		F = 10.31 (significant at the .001 level)	

TABLE A3. Exogeneity test results.

	Hausman test results	
	H_0: Q is exogenous	
	Environmental	Nonenvironmental
P value	0.274	0.006
Result	Fail to reject H_0	Reject H_0

Intergovernmental Panel on Climate Change models. The expected increase in aridity and interannual variance of water supplies will induce more interest in environmental water leases. Even without climate change, tree-ring reconstructions of historic flow levels in the arid western United States show that extreme prolonged droughts occur regularly (Meko et al. 2007). As water managers plan for extended drought, information on how water lease prices respond to dry and wet conditions will be useful. Increasing costs of building dams and water conveyance systems (both capital costs and environmental costs) make voluntary transactions to acquire water a relatively more attractive option, and models such as those developed here can provide valuable insight on patterns in water markets.

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APPENDIX

First-Stage Regression and Exogeneity Test Results

First-stage results from the two-stage least squares regression models are presented in Tables A1 and A2. Exogeneity test results are presented in Table A3.

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Dendrochronology and links to streamflow

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SUMMARY

Streamflow variability on timescales of decades to centuries becomes increasingly important as water managers grapple with shortages imposed by increasing demand and limited supply, and possibly exacerbated by climate change. Two applications of dendrochronology to the study of flow variability are illustrated for an existing 1244-yr reconstruction of annual flows of the Colorado River at Lees Ferry, Arizona, USA: (1) identification and climatological interpretation of rare flow events, and (2) assessment of vulnerability of water-supply systems to climatic variability. Analysis centers on a sustained drought of the mid-1100s characterized by persistent low flows on both the Colorado and Sacramento Rivers. Analysis of geopotential height anomalies during modern joint-droughts suggests more than one mode of circulation might accompany joint-drought in the two basins. Monte Carlo simulation is used to demonstrate that a drought as severe as that in the 1100s on the Colorado River might be expected about once in every 4–6 centuries by chance alone given the time-series properties of the modern gaged flows. Application of a river-management model suggests a mid-1100s-style drought, were it to occur today, would drop reservoir levels in Lake Mead to dead-pool within a few decades. Uncertainty presents challenges to accurately quantifying severe sustained droughts from streamflow reconstructions, especially early in the tree-ring record. Corroboration by multiple proxy records is essential. Future improvements are likely to require a combination of methodological advancements and expanded basic data.

1. Introduction

Dendrochronology is linked to streamflow through the common responses of tree-growth and streamflow to variations in net precipitation and runoff (Stockton and Jacoby, 1976). The statistical relationship between time series of tree-ring indices and streamflow has been exploited for multi-century reconstructions of flow for river basins in many parts of the world (e.g., Akkemik et al., 2004; Gou et al., 2007; D'Arrigo et al., 2009; Liu et al., 2010). The methodology and applications of streamflow reconstruction from tree rings have been reviewed by Loaiciga et al. (1993) and Meko and Woodhouse (2011).

Nowhere has the attention to streamflow reconstruction been more focused than in the Colorado River basin, a key source of water supply for some 30 million people in the western United States. Climate change and variability are critical issues in this basin. Mean annual flows of the Colorado River are over-allocated by the 1922 Colorado River Compact governing the distribution of water (MacDonnell et al., 1995); demand is expected to continue increasing (National Research Council, 2007); climate-change projections envision imminent drying over the next century (Seager et al., 2007b); and Lake Mead, a major reservoir, is at its lowest level since it began filling in the 1930s (Barringer, 2010). Projected climate change is expected to result in substantial decreases in runoff and further drops in reservoir levels by the end of the 21st century (e.g., Christensen and Lettenmaier, 2006; McCabe and Wolock, 2007; Barnett and Pierce, 2008; Rajagopalan et al., 2009).

The history of Colorado River water woes is closely linked to the development of the science of dendrohydrology in the United States. Schulman (1945) established the physical rationale for reconstruction in assessing water-supply variability of the Colorado for Los Angeles Power and Light. Stockton and Jacoby (1976) first applied modern multivariate statistical methods to reconstruction in extending the Colorado River flows at Lees Ferry, Arizona to A.D. 1520. Subsequent tree-ring studies of reconstructed flow on the Colorado have aimed at improvement of accuracy, temporal extension, climatological interpretation and water-management applications. Approaches to increasing the accuracy have included varying the makeup of the tree-ring network and exploring new methods of statistical reconstruction modeling (e.g., Michaelsen et al., 1990; Hidalgo et al., 2000; Woodhouse et al., 2006; Gangopadhyah et al., 2009). Climatological interpretation has been directed toward examination of ocean-atmosphere drivers of reconstructed flow variations (e.g., Woodhouse et al.,

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2006, 2010). Water managers have long referred to reconstructions as precautionary evidence of extended droughts on the Colorado, but have only recently explored direct use of reconstructions as input to river-management models (Prairie et al., 2008).

In this paper we analyze the longest existing reconstruction for the Colorado River (Meko et al., 2007) to investigate ways the extended flow record can provide additional information on current and future droughts. We frame the analysis around a particular paleo-drought, a multi-decadal period of recurrent low flows in the mid-1100s (Meko et al., 2007). This low-flow period occurred during a medieval period (A.D. 800–1400) characterized by unusually persistent droughts in western North America and large hydroclimatic anomalies in other parts of the globe (Seager et al., 2007a). The ongoing drought, now entering its second decade (Woodhouse et al., 2010) could represent a return to an amplified low-frequency mode of hydroclimatic variability. Here we explore various aspects of the persistent low-flow period in the mid-1100s on the Colorado River: spatial extent and climatology, water-supply implications, and likelihood of recurrence. We also discuss challenges to interpretation cast by uncertainty. Novel aspects of this paper include a simulation-based approach to a probabilistic context of an exceptional persistent paleo-drought, and application of a long-term river planning model to explore potential impacts on management were such a drought to occur in the future.

2. Data

Tree-ring data points and basins are shown on the map in Fig. 1. Reconstructions analyzed include A.D. 762–2005 annual (water-year) flows of the Colorado River at Lees Ferry Arizona (Meko et al., 2007) and A.D. 869–1977 annual flows of the Sacramento River (Meko et al., 2001); both reconstructed time series were downloaded from the International Tree-Ring Data Bank (ITRDB) (http://www.ncdc.noaa.gov/paleo/treering.html). To illustrate aspects of uncertainly in the Colorado River reconstruction, use is also made of calibration-period (post-1905) segments of sub-period, or time-nested, reconstruction models described in Meko et al. (2007). These time series, not available from the ITRDB, were obtained from the files of the main author.

Historical time series of natural flows (flows adjusted for depletions and reservoir storage) for years 1906–2009 were obtained for the Colorado and Sacramento Rivers in the western United States. Flows summed over the water-year for the Colorado River at Lees Ferry, Arizona, were downloaded from the US Bureau of Reclamation (http://www.usbr.gov/lc/region/g4000/NaturalFlow/). Flows for the Sacramento River were downloaded from the California Department of Water Resources (http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST).[1] All observed and reconstructed natural-flow series used in this paper are included in the Supplemental Materials. Gridded reconstructed summer (JJA) Palmer Drought Severity Index (PDSI) for North America for the past 2000 yr were obtained from Cook et al. (2010).

Unless otherwise noted, flow units on plots are either km^3 or percentage of "normal", defined here as the 1906–2005 observed mean. Some results are also presented parenthetically in million acre-feet (maf) for the benefit of water managers. Normal flow for the Colorado River at Lees Ferry is 18.6km^3, or 15.1 maf; and for the Sacramento River is 22.4km^3, or 18.0 maf.

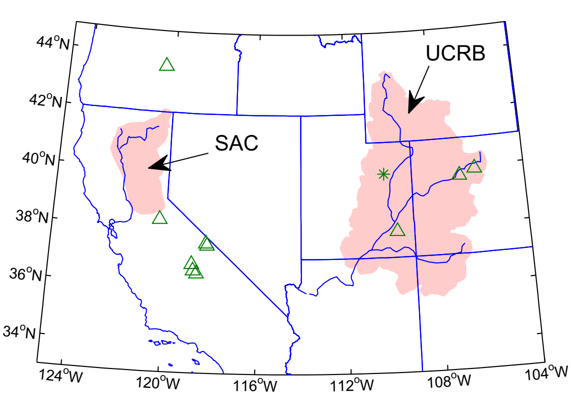

Fig. 1. Map of river basins and tree-ring sites. Sites plotted are Harmon Canyon (∗) and early-1100s tree-ring networks (△) for reconstructions of flow in Upper Colorado River Basin (UCRB) (Meko et al., 2007) and Sacramento River Basin (SAC) (Meko et al., 2001).

3. Methods

Low-frequency time series variations were summarized by a 25-yr running mean and by Gaussian filtering. The Gaussian filter is a symmetric, bell-shaped filter with positive weights that sum to 1. We used guidelines in Mitchell et al. (1966) to design a Gaussian filter with approximately the same wavelength of 50% frequency-response (Panofsky and Brier, 1968) as the 25-yr running mean. This is a 33-weight Gaussian filter, which when used for smoothing weights 33 successive years of a time series with highest weight on the central year of the filtered segment; the filter-weights are listed in the Supplemental Material.

Covariation of pairs of time series was summarized by correlation analysis and spectral analysis. Correlation coefficients were tested for significance (Haan, 2002) after adjusting sample-size for effect of autocorrelation (Dawdy and Matalas, 1964). Covariation as a function of frequency was summarized with cross-spectral analysis using the smoothed periodogram as a spectral estimator (Bloomfield, 2000). Steps in spectral estimation were (1) removal of mean, (2) tapering of 5% of each end of the series, (3) padding with zeros to a length the first power of 2 larger than the original series length, (4) raw-periodogram computation by the fast Fourier transform, and (5) smoothing of periodogram with a set of Daniell filters (Bloomfield, 2000) to get a spectrum of desired smoothness and bandwidth. Cross-periodograms and related quantities — squared coherency and phase — were similarly computed using procedures described in detail by Bloomfield (2000) and implemented previously in a tree-ring study by Meko and Woodhouse (2005).

Synthetic time series of observed flow were generated by exact simulation (Percival and Constantine, 2006), using the circulant embedding method of Dietrich and Newsam (1997), to explore how anomalous the most extreme drought of the tree-ring record is given the time-series properties of flow in the gaged record. Exact simulation preserves the spectral properties of the observed series and has the advantage of not requiring an assumption of a parametric generating mechanism (e.g., autoregressive process). Our non-parametric spectral estimator was the raw periodogram, computed as described in the preceding paragraph, except that for the selected circulant-embedding method zero-padding to the next-highest power of 2 larger than four times the original series length was required to supply simulations of the desired length. As normality is an assumption in the exact simulation method of Percival and Constantine (2006), a Lilliefors test (Conover, 1980) was applied to check that time series used to develop simulations are approximately normal. To check sensitivity of probabilities to simulation method we repeated the simulation analysis with synthetic flows generated by a first-order autoregressive (AR(1)), or Markov, process (Haan, 2002). For AR(1) modeling, the model is

[1] This series is referred to online as "Sacramento Valley Runoff", Water-Year Sum

$x_t = \alpha x_{t-1} + \epsilon_t$, where x_t is flow as departure from the mean in year t, α is the autoregressive coefficient, and ϵ_t is the noise term.

Assessment of water-management impact of severe drought was illustrated with the help of the Colorado River Simulation System model (CRSS). CRSS is the official model used by the US Bureau of Reclamation for long-term planning (Fulp, 2003) and represents the Colorado River system using a series of linked objects that interact with each other based on a set of user-specified rules (Zagona et al., 2001). We used the most recent version of CRSS (January 2010), which is current for operating policies and demand schedules. CRSS requires hydrologic input at a monthly timestep for 29 control points located throughout the Colorado River Basin. Accordingly, the Meko et al. (2007) streamflow reconstruction at Lees Ferry was disaggregated both temporally and spatially using the same approach employed by the Bureau of Reclamation (Prairie et al., 2007).

Upper air circulation patterns associated with joint-droughts on the Sacramento and Colorado Rivers were evaluated with composite maps of 500-mb height anomalies. Images of divisional-average PDSI and geopotential height anomalies during joint-droughts were generated with the online Web tool of the NOAA/ESRL Physical Sciences Division, Boulder Colorado (http://www.esrl.noaa.gov/psd/).

4. Return periods of rare flow events

The A.D. 762–2005 reconstruction for the Colorado River at Lees Ferry is a more than tenfold increase over the period of observed natural flows, which begins in 1906 (Fig. 2). One advantage of such extension is an increased chance of sampling uncommon flow features, or rare events, not represented in the short snapshot of observed flows. Extremes are especially sensitive to length of sample. The sample represented by the instrumental period on the Colorado, for example, happens not to include the lowest single-year reconstructed flow, 1685 (Fig. 2). Multi-year droughts consisting of very-low flows clustered over several years, or of slightly-low flows persisting over decades without intervening high flows, are potentially important to water-resources management on the Colorado because such droughts can exhaust the existing reservoir storage. An example of a rare multi-year event of the latter type in the tree-ring record of the Colorado River is the mid-1100s drought highlighted by Meko et al. (2007) as the lowest 25-yr running mean, 15.5 km^3 (12.6 maf or 83.8% of normal), in the 1244-yr reconstruction covering years A.D. 762–2005. In comparison, the lowest 25-yr running mean observed flow in the 104-yr period 1906–2009 was 16.1 km^3 (13.1 maf or 86.9% of normal), which occurred in 1953–1977. The 25-yr window happens to highlight intensity of multi-decadal drought in the Meko et al. (2007) reconstruction, but also has direct relevance to existing management: 1953–1977 is one of two "critical drought periods" designated on the Colorado River by the US Bureau of Reclamation and traditionally used in drought risk-assessment (personal communication, Russell Callejo). [2]

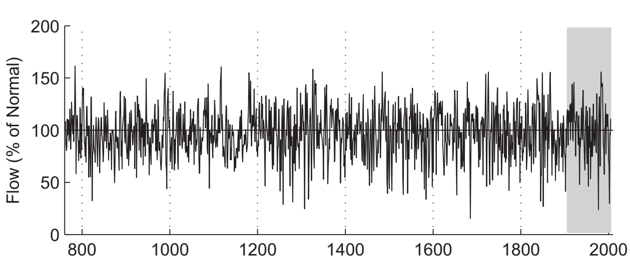

Fig. 2. Time plot of reconstructed annual flows of Colorado River, A.D. 762–2005. Period of available observed flows shaded. Source of data: Meko et al. (2007). "Normal" is 1906–2005 observed mean (see Section 2).

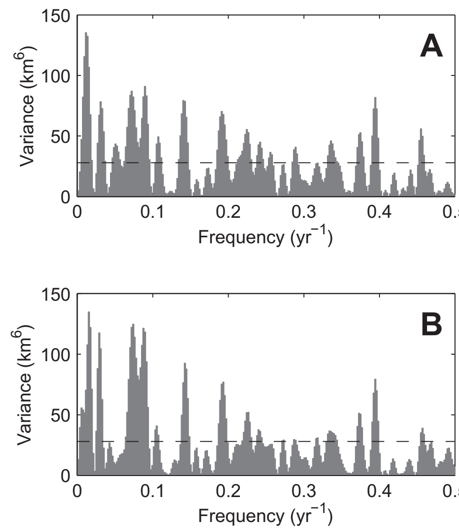

Fig. 3. Periodograms of Colorado River flows used for exact simulations. (A) 1906–1999 observed flows, and (B) 1906–2009 observed flows. Horizontal line at variance of time series (white-noise spectrum).

The mid-1100s drought, can be viewed conceptually as (1) a signal for a changing mechanism of climate/hydrology, or (2) unchanging variability sampled in an expanded time window. Which view is correct is impossible to determine, but simulations can help estimate the chance of those features occurring given the current driving mechanisms. The tree-ring record suggests a probability of $p \approx 1/12$, or $p \approx 0.08$, of a 25-yr mean flow less than 83.8% of normal in any given 104-yr period (approximately 12 such periods in 1244 yr). We defined a "critical drought" as a 25-yr mean lower than 83.8% of normal and used simulations of observed flows to estimate how likely a critical drought would be if many 104-yr sequences of observed flows were available instead of the single snapshot of 1906–2009. The simulation exercise consisted of the following steps:

1. Generate 10,000 simulated series of flows of length 104 yr by exact-simulation (see Section 3)
2. Count the number of simulations N_c with at least one critical drought
3. Estimate the probability of a critical drought in any 104-yr period as $p_c = N_c/10{,}000$

Simulations were repeated on observed flows for 1906–1999 and 1906–2009 to test sensitivity of simulations to the record low-flows of 2000–2009 (Woodhouse et al., 2010). The exercise was repeated by exact simulation and AR(1) simulation to test sensitivity to assumption of generating mechanism. The Lilliefors test indicated both series were approximately normally distributed, and thus suitable for exact simulation. The periodogram, the framework for our implementation of exact simulation, is broadly low-frequency in appearance for both series (Fig. 3). Both series have high variance at $f \approx 0.07$–$0.09\ \mathrm{yr}^{-1}$, or wavelengths 14–11 yr. The effect of the 2000–2009 segment of observed flows is most noticeable as increased variance in that frequency-range and also at $f \approx 0.027$–$0.032\ \mathrm{yr}^{-1}$, or wavelengths 37–31 yr. The underlying shapes of the periodograms (which are unsmoothed

[2] A "critical drought period" is a sequence of dry years, identified from existing flow records, as a worst-case scenario for water management.

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spectra), are consistent with autoregressive processes. Both series are positively autocorrelated, and fitted AR(1) models have estimated coefficients, $\alpha = 0.24$ for 1906–1999 and $\alpha = 0.27$ for 1906–2009, that differ from zero by more than two standard errors.

The exact simulations give higher probability of critical drought than suggested by the one occurrence in the 12-century reconstruction, and suggest one such drought might be expected about once every six centuries ($p \approx 0.17$) from 1906 to 1999 flows, and once every four centuries ($p \approx 0.28$) from 1906 to 2009 flows (Fig. 4). The higher probability of critical drought for the longer observed record probably reflects the greater low-frequency variance evident in the periodogram for the 1906–2009 series (Fig. 3) and possibly also the slightly lower mean flow of the 1906–2009 segment (18.50 km^3 versus 18.63 km^3). AR(1) simulation gives lower probabilities than exact simulation. This difference suggests simulation method can make an important difference in estimated probability of critical drought. Exact simulation has the advantage of flexibility in modeling the complicated spectral structure of observed flows (Fig. 3), and for that reason we favor the exact-simulation results over those from AR(1) simulation for these particular time series. For the 1906–2009 segment, however, even the AR(1) simulations yield a higher probability of critical drought than suggested by the long-term reconstruction.

Simulation results suggest the extreme reconstructed 25-yr mean flow of the mid-1100s has a reasonably high chance of recurrence without invoking changes in the modern statistical framework of observed flows. Failure to observe such a drought in the 1906–2009 record is likely a phenomenon of a short sample. A caveat is that the probabilities associated with the simulation exercise just described depend the specific definition of critical drought. A low 25-yr running mean is just one characteristic of the mid-1100s drought described by Meko et al. (2007). Simulation exercises defining drought differently (e.g., number of consecutive years without any "high" flows) could lead to different assessments of "uniqueness" of the 1100s paleo-drought.

Future tree-ring collections of ancient wood in the Colorado basin will likely lead to improved accuracy of flow reconstruction and possibly to re-assessment of drought severity in the mid-1100s. The model generating the A.D. 762–1182 portion of the reconstruction plotted in Fig. 2 has $R^2 = 0.60$. A reconstruction with a higher R^2 would have higher variance, and so a tendency for greater extremes of running means, and this might be expected to yield a lower estimated smoothed flow in the mid-1100s. This result is not guaranteed, however, as lower error variance does not imply that *any particular* reconstructed time series feature will be amplified as a departure from the mean.

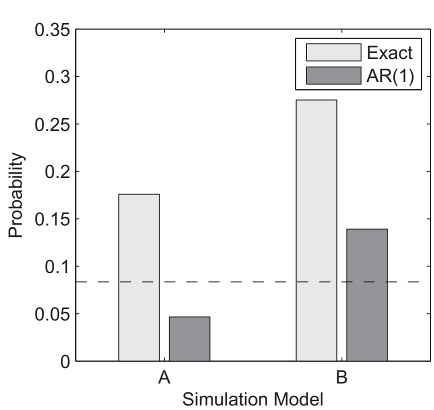

Fig. 4. Simulation-based probabilities of an 1100s low-flow in any 104-yr period. Simulations by exact simulation and first-order autoregressive (AR(1)) modeling of (A) 1906–1999 observed flows, and (B) 1906–2009 observed flows. Dashed line marks empirical probability from 1244-yr tree-ring reconstruction. See Section 4 for definition of 1100s low-flow.

5. Spatial aspects and mechanisms of severe drought

Clues to the climatology of the mid-1100s Colorado River drought are provided by the rich archive of millennial-length tree-ring data for the western United States. In this section we exploit two particularly useful products of this archive: an A.D. 869–1977 reconstruction of the annual flows of the Sacramento River (Meko et al., 2001), and gridded reconstructions of PDSI in the North America Drought Atlas (Cook et al., 2007, 2010). A similar approach to studying mechanisms of past drought in the region on a shorter time scale has previously been taken by Meko and Woodhouse (2005).

The flow reconstructons for the Sacramento and Colorado rivers cover a common period of A.D. 869–1977 and were made possible by the profusion of long drought-sensitive tree-ring chronologies in the Sierra Nevada of California and the Rockies of Colorado. The annual flows of the two rivers are significantly positively correlated, though correlations are small (Table 1). Inter-basin correlation is similar for the observed and reconstructed flows in the 1906–1977 period in common for both types of data. For the longer reconstruction common period (A.D. 869–1977) correlation drops slightly but is even more statistically significant due to the increased sample-size.

Flow anomalies at the decadal scale are large enough to be practically significant in these basins. For example, the range in 25-yr running means of observed flows expressed as a percentage of the 1906–2005 mean is 87–117% on the Colorado and 83–110% on the Sacramento. Smoothed time plots of reconstructed flows show occasionally large in-phase and out-of-phase behavior (Fig. 5). A similar picture of covariation is given by the running mean and Gaussian smoothing. Both smoothed series flag the mid-1100s periods for unusually strong spatial coherence of low flows.

Joint-drought in these two large basins suggests an associated large-scale anomaly in atmospheric circulation and moisture delivery, presumably in the cool season, as the hydrology of both basins is strongly snowmelt-driven. Because multi-decadal joint-droughts are not represented in the 20th and 21st centuries, climatological data for a diagnostic study is lacking. Nevertheless, the mechanism of persistent joint-drought in these critical water-supply basins is an important topic for climatology and hydrology, and the phenomenon of joint-drought at shorter time scales can be investigated with upper-air geopotential height data extending back over more than 50 yr.

While the upper Colorado and the Sacramento River basins share 1977 as the most severe single-year drought in the instrumental period, the most severe multi-year drought occurs at different times in the two basins: the 2000s in the Colorado, and the 1930s in the Sacramento. The late 1980s to early 1990s, however, was a significant period of persistent low flow in both basins. During the period 1988–1992 average annual flows were 72% of

Table 1
Pearson correlation between annual flows of Sacramento and Colorado Rivers.[a]

	Period	r[b]	N[c]	N_e[d]	p-value[e]
Obs	1906–2009	0.44	104	99	5.0E−6
	1906–1977	0.37	72	70	1.5E−3
Rec	1906–1977	0.32	72	70	7.6E−3
	869–1977	0.22	1109	1048	1.0E−12

[a] Natural flows, as described in Section 2.
[b] Correlation over indicated period.
[c] Length of period (yr).
[d] Effective length of period (adjusted for lag-1 autocorrelation).
[e] Probability of Type I error in two-tailed test of null hypothesis of zero population correlation.

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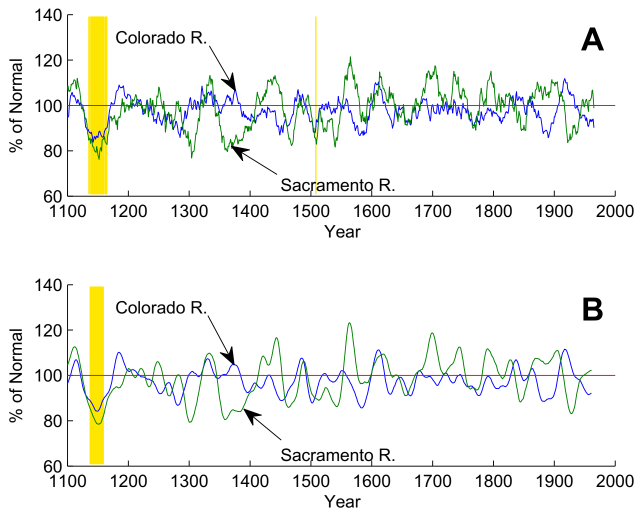

Fig. 5. Smoothed reconstructions of annual flows of Colorado River and Sacramento River. (A) Smoothing by 25-yr running mean. (B) Smoothing by 33-weight Gaussian filter. Periods two series simultaneously in lowest decile shaded. "Normal" is 1906–2005 observed mean (see Section 2). Data sources: Meko et al. (2007) and Meko et al. (2001).

normal in the upper Colorado River basin and 56% of normal in the Sacramento River basin.

The North America Drought Atlas (Cook et al., 2007, 2010) can be used to compare spatial patterns of drought in recent decades with patterns reconstructed from tree rings for the mid-1100s. Despite a mismatch of seasons, summer-average (JJA) PDSI patterns are relevant to streamflow in the snowmelt-driven Colorado and Sacramento basins because in the southwestern USA summer PDSI is strongly correlated with cool-season moisture anomalies (Cook et al., 2007; St. George et al., 2010). The drought of water-year 1977 by this summer PDSI metric was widespread across the western USA (Fig. 6a). Atmospheric circulation over the cool season was characterized by a meridional flow pattern with a strong center of high pressure over Pacific Northwest coast of the USA, extending over much of western North America (Fig. 6b). This area of high pressure effectively blocked the jet steam from most of the USA except for far southern portions.

The drought of the 1988–1992 displays a pattern of dryness that extends from California northeast to the northern Great Plains (Fig. 7a). Colorado is on the fringe of this drought, but the headwaters of the Colorado River clearly experienced its influence. Circulation patterns for this period of time are marked by a band of high pressure across eastern Asia, the North Pacific Ocean, and North America (Fig. 7b). Low pressure is restricted to high northern latitudes. A broad ridge is located over the Pacific coast, and the path of the jet stream is over northern North America. The onset of this drought coincided with a cold ENSO event, with below average sea surface temperatures in the equatorial Pacific and the jet stream position north of its typical path (Trenberth et al., 1988). These cold equatorial Pacific conditions did not persist, but the high pressure over western North American continued throughout the years of the drought. This period was also one of widespread drought over much of Europe, with unprecedented impacts on aquifers in lowland areas of the United Kingdom (March and Monkhouse, 1993) perhaps due to strong positive phase of the Northern Atlantic Oscillation.

An exploratory analysis of pattern correlations of reconstructed-PDSI maps for the mid-1100s with observed-PDSI maps of the 20th century did not identify the joint-drought years of 1977 or 1988–1992 as especially strong analogs for years 1138–1160 (joint-drought core in Fig. 5). In general, drought over this

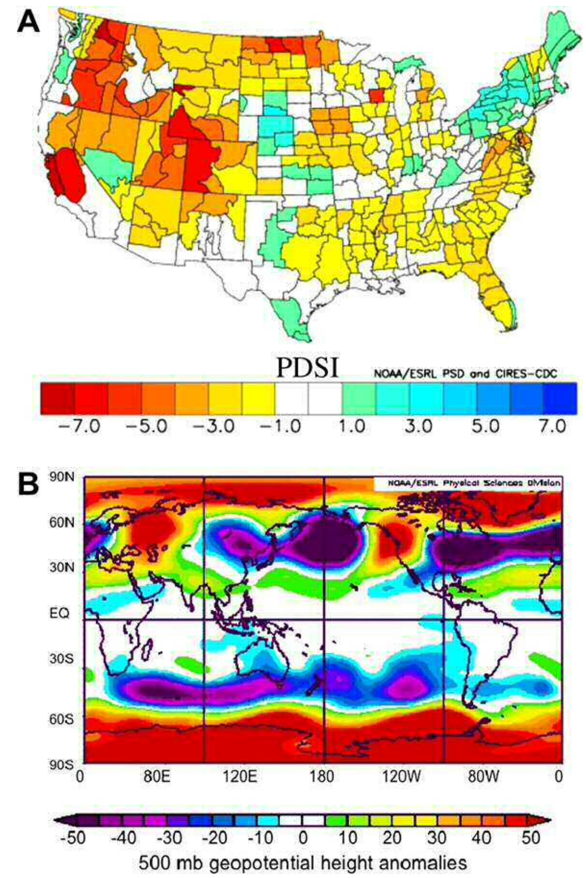

Fig. 6. Drought pattern and circulation anomalies in 1977. (A) Climate Division summer (JJA) Palmer Drought Severity Index, (B) November–March 500 mb geopotential height (m) anomaly from 1968 to 1996 average. Images provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado from their Web site at http://www.esrl.noaa.gov/psd/.

interval is widespread through the southwestern and southern USA, although a few individual years (e.g., 1147 and 1154) show the diagonal pattern of drought from southern California to the north-central USA (Fig. 8). The Atlas may however be poorly suited for this type of diagnostic analysis because of limitations in the tree-ring site coverage in the 1100s (in particular, data are lacking for the northern Great Plains, a center of drought in 1988–1992) and the blurring of seasonal climate anomalies over multiple seasons in summer-average PDSI. In summary, the two severe short-period joint-droughts (Colorado–Sacramento), which share somewhat similar patterns of drought, and for which upper air height anomalies are available, are characterized by strongly differing patterns of 500-mb height anomaly. That the circulation patterns are dissimilar points to the complexity of unraveling causes of drought. The general drought pattern for 1977 and 1988–1992 is not common during the 1100s drought, which may be largely due to sparseness of data in key regions. Whether controls on drought in the mid-1100s were analogous to controls on more recent droughts is difficult to say, but may become more evident with increased tree-ring coverage over North America through the medieval period.

6. Water-supply vulnerability

Large river basins in semi-arid regions are often so heavily developed that the impact of climate variation on water supply can be estimated only with the help of river-management models that incorporate the various components of water transfer, storage

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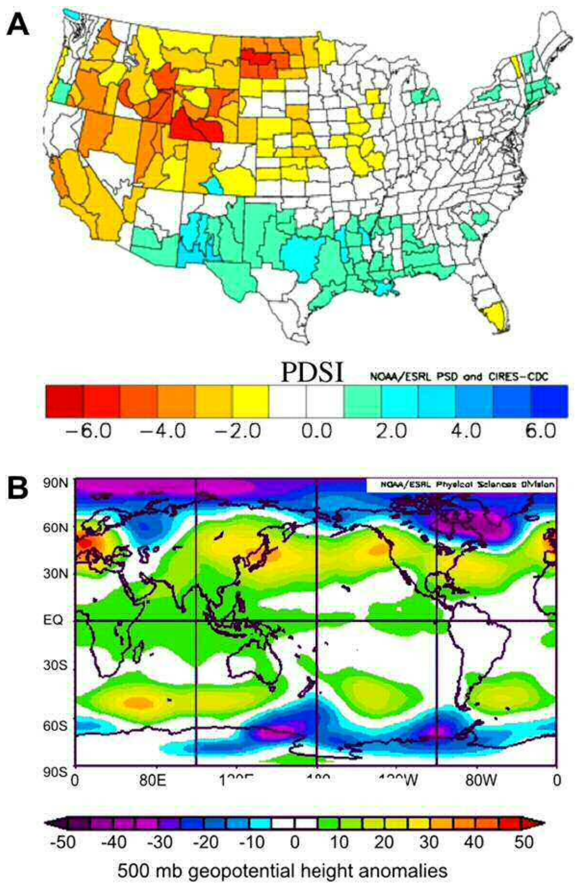

Fig. 7. Composite drought pattern and circulation anomalies in 1988–1992. Remainder of caption as in Fig. 6.

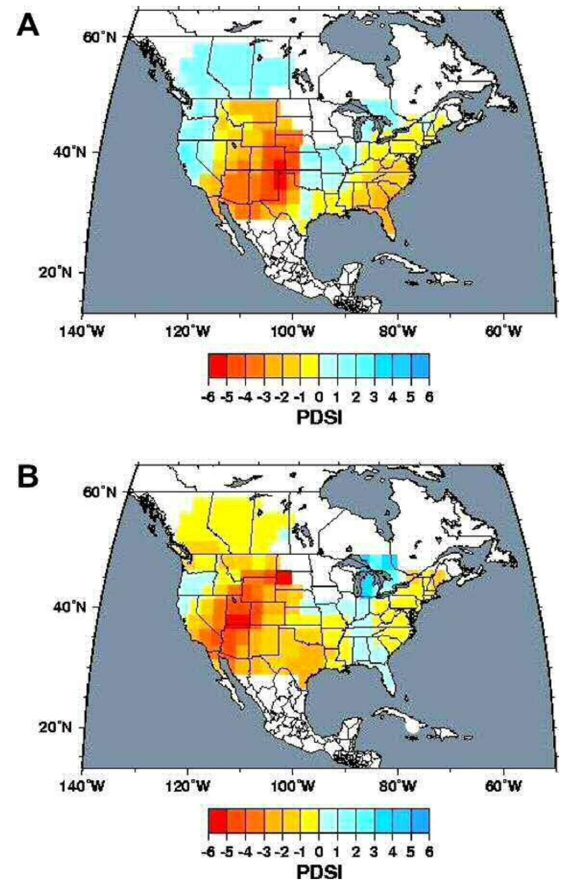

Fig. 8. Tree-ring-reconstructed PDSI in two years of joint Colorado–Sacramento drought of mid-1100s. (A) 1147, (B) 1154. Gridded summer-average (JJA) PDSI from Cook et al., 2010.

and demand. On the Colorado River, the official model for long-term planning is the Colorado River Simulation System model, or CRSS (Fulp, 2003). This model can be used to simulate how system storage responds to various hydrologic inputs.

One approach to using paleo-data in water-management models is to run scenarios from the flow reconstruction as input sequences. In assessing drought sensitivity, it is desirable to choose a period of anomalously low flow. The severe drought of the 1100s has already been mentioned as a rare multi-decadal feature in hydrologic drought in the western United States. A color-mapped plot of anomalies in running means of reconstructed flow highlights this period, and indicates the unique feature of that drought is longevity rather than short-period intensity (Fig. 9).

We selected the 25-yr period with the lowest mean streamflow as input to CRSS and targeted Lake Mead elevation over the management horizon of 2010–2034 as an indicator of system response. To put this extreme drought into perspective, we also selected the 49 next-lowest 25-yr periods as input into CRSS. Mean streamflow for this subset of 50 paleo-data sequences ranged from 15.5 km^3 (12.6 maf) to 16.3 km^3 (13.2 maf), or from 84% to 88% of normal flow. Low-flow periods occurred in seven distinct groups of overlapping sequences which were distributed throughout the paleo-record (see Fig. 9 where orange streaks intersect the dashed line). The maximum level of overlap within groups containing at least two sequences was 96% (when sequences where offset by a single year); whereas, the minimum level ranged from 8% to 92%.

Lake Mead response to the extreme drought sequence of the 1100s is an initial rapid decline in elevation; two of three shortage trigger elevations are breached within the first 5 yr (Fig. 10). By the early 2030s, Lake Mead elevation is approximately at dead-pool elevation (273 m, 895 ft) and remains there until the end of the analysis period. The ensemble of traces produced by the other sequences show that the hydrologic input from the extreme drought sequence does not consistently result in the lowest Lake Mead elevations (Fig. 10), indicating that more intense short-term droughts are embedded within the other low-flow sequences. Relative to these sequences, however, the mid-1100s drought stands out as having no periods of substantive recovery; Lake Mead elevations are either declining or stable.

7. Uncertainty

Uncertainty is an obstacle to the acceptance of streamflow reconstructions by water managers and to the application of reconstructions in water-resources research. The Colorado River reconstruction of Meko et al. (2007) happens to be a relatively strong regression-based reconstruction: reconstructed flows closely track observed fows, and accuracy as measured by regression R^2 ranges from 77% for the segment beginning in A.D. 1365 to 60% for the segment beginning in A.D. 762 (Fig. 11). The degradation of signal back in time is characteristic of reconstructions generated by time-nested models and is a natural consequence of sparse sample coverage of the watershed in the early part of the tree-ring record. The limitation on inferences of flows in the mid-1100s can be appreciated from the tree-ring networks shown in Fig. 1. The Sacramento is problematic because none of the mid-1100s tree-ring sites are within the basin. The tree-ring sites for the Colorado

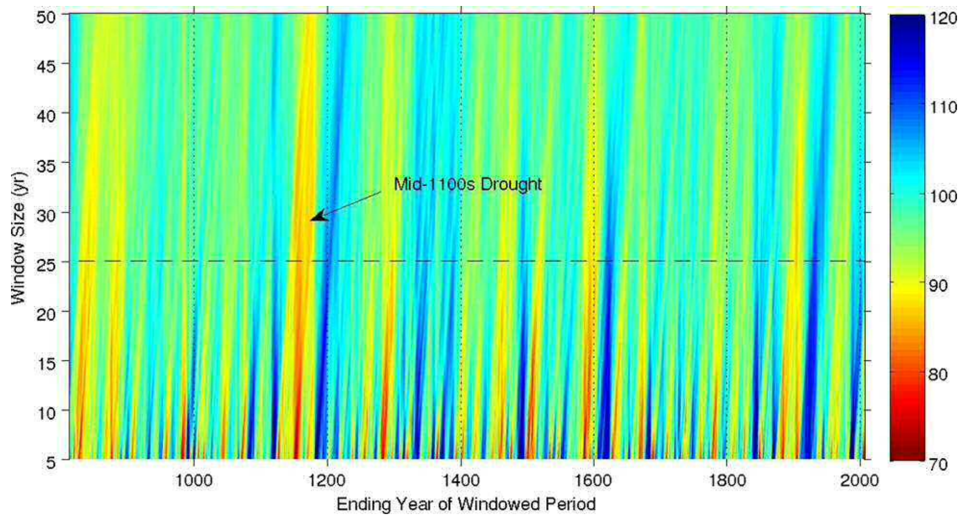

Fig. 9. Color-mapped running means of reconstructed Colorado River flow. Running means of length 5–50 yr mapped on ending year of period. Periods of low 25-yr runnings, say, correspond to yellow-red patches along the dotted line. Color-mapped quantity is percentage of 1906–2005 observed mean (Section 2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

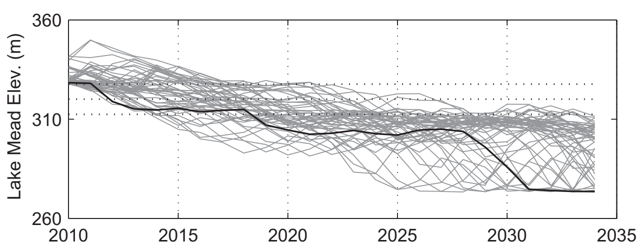

Fig. 10. Ensemble of traces showing Lake Mead elevations for a set of hydrologic input sequences from the paleo-record. Bold line is the 25-yr period with the lowest mean streamflow; other traces show Lake Mead response to 49 25-yr periods with the next-lowest mean streamflow. Shortage trigger elevations are shown by dotted lines and signal delivery reductions to the Lower Basin states in amounts defined by the most recent Colorado River management guidelines (US Department of the Interior, 2007).

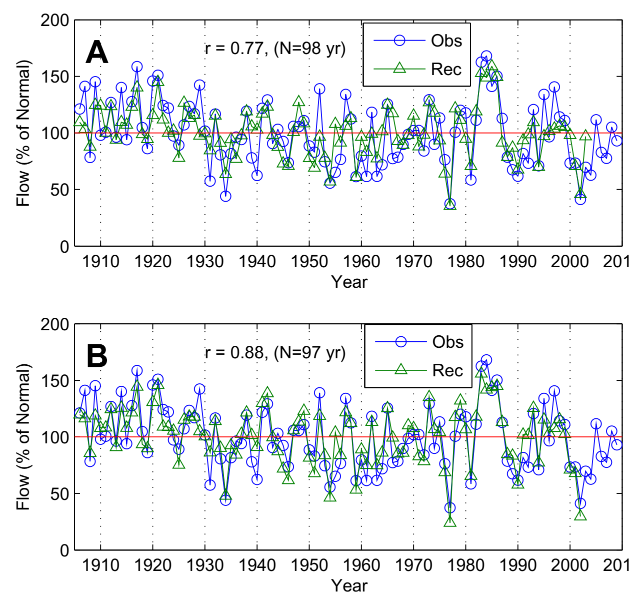

Fig. 11. Time plots of observed and reconstructed Colorado River flows for two sub-period reconstruction models. (A) M762, calibrated on 1906–2003 and used for flows A.D. 762–1182. (B) M1365, calibrated on 1906–2002 and used for flows A.D. 1365–2002. Units are percentage of observed mean (see Section 2). Correlation for period of calibration annotated.

reconstruction are somewhat more favorably situated along the axis of the main stem of the river, but the Green and San Juan sub-basins are not represented in the 1100s network.[3]

When low-frequency features, such as the 1100s drought, are of primary interest, it is important to check that the accuracy implied by regression R^2 applies to the low frequencies. A coherency plot from cross-spectral analysis of observed and reconstructed flows shows that the signal at low frequencies is relatively strong for Colorado River model M762 (the applicable model for the mid-1100s part of the reconstruction), and that frequencies with high coherency generally are those with high variance in the individual series (Fig. 12). The phase diagram in Fig. 12 further supports that variations at those frequencies corresponding to wavelengths longer than about a decade are in-phase. This result lends some support for the ability of the tree-ring record to reflect persistent droughts like that of the A.D. 1100s.

It is important to emphasize that R^2 and other regression statistics do not summarize all aspects of uncertainty in a tree-ring reconstruction of streamflow. It has long been recognized that the detrending of measured ring-width series in standardizing tree-ring data puts a limits on the maximum wavelength of climate variation that can be identified (Cook et al., 1995). Climate fluctuations at wavelengths longer than the longest lifespan of individual trees in a chronology will consequently be missing from tree-ring data standardized by conventional methods. Improvement in identification of low-frequency climate signals is an active research topic in dendroclimatology (Esper et al., 2003; Melvin and Briffa, 2008; Briffa and Melvin, 2011).

Regression statistics also fail to account for possible differences in the sample-depth and makeup of tree-ring chonologies in the calibration period of the regression model and the distant past. This point is illustrated for Harmon Canyon, a *Pseudotsuga menziesii* chronology in northeastern Utah (Fig. 1). None of the sampled trees in this chronology cover both the 20th century and the period prior to A.D. 1200, and sample-depth drops off consideraby in the early part of the tree-ring record (bottom, Fig. 13). It is necessary in

[3] The maps in Fig. 1 show only those tree-ring sites available for the mid-1100s parts of the reconstructions. Later parts of reconstructions have increased site density.

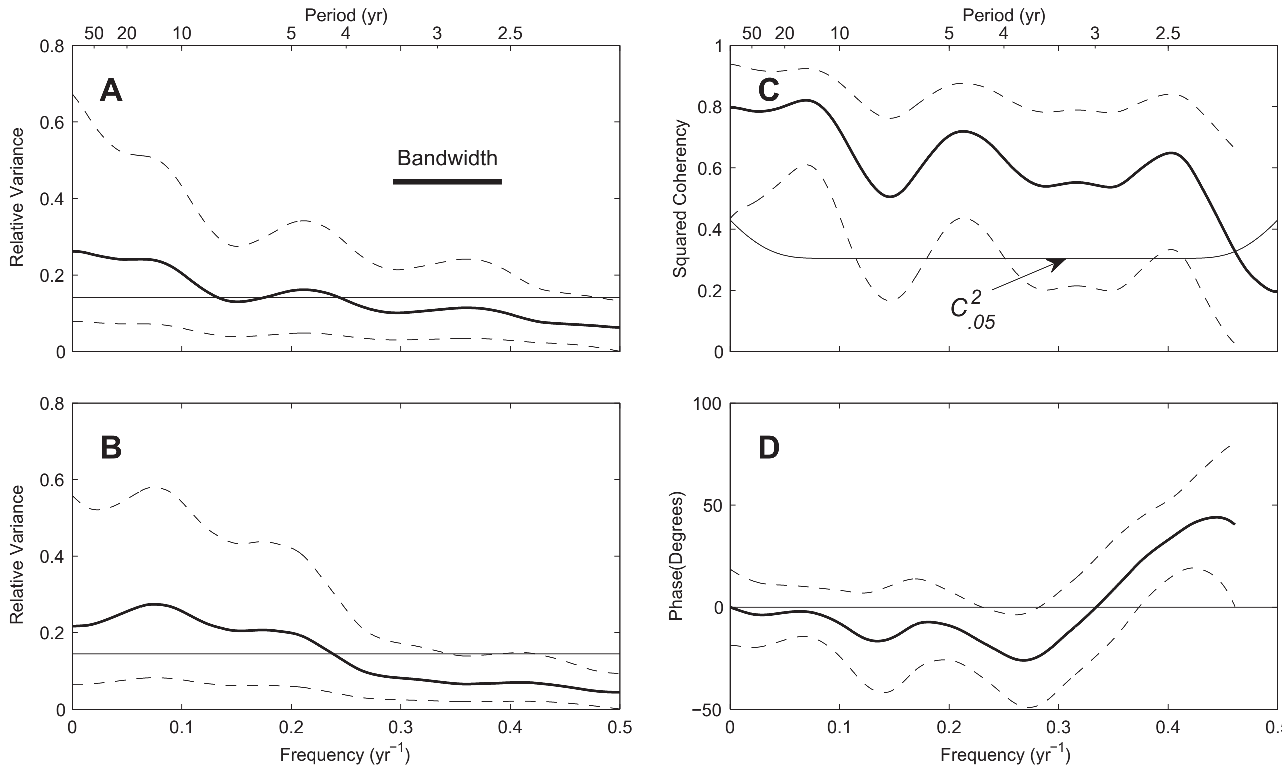

Fig. 12. Cross-spectrum of observed with reconstructed Colorado River flows, 1906–2005. (A) Normalized spectrum of observed flows. (B) Normalized spectrum of reconstructed flows. (C) Squared coherency of observed with reconstructed flows. (D) Phase of observed with reconstructed flows. Horizontal lines in (A) and (B) are theoretic white-noise spectra. Solid line labeled $C^2_{.05}$ in (C) is simplified threshold for 95% significance of squared coherency (Bloomfield, 2000). Dashed lines in all plots are 95% confidence intervals.

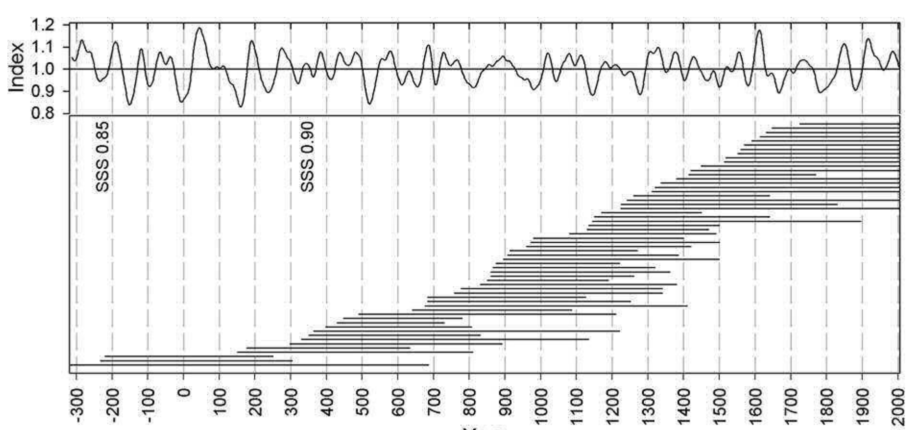

Fig. 13. Smoothed time series and sample-depth chart for Harmon Canyon, Utah, tree-ring chronology. (Top) Standard tree-ring index smoothed with spline to emphasize multi-decadal departures. (Bottom) Time coverage by individual tree radii. SSS, or sub-sample signal strength, measures ability of chronology with given sample-size to capture signal of chronology with full sample-size. Figure from Knight et al., 2010.

applying such a chronology to streamflow reconstruction to assume that the quality of streamflow signal is similar in the living trees and the remnant-wood samples, and reasonable to assume that uncertainty will be amplified in those parts of the record represented by few trees.

An important part of the streamflow-reconstruction process is independent validation of important features of flow reconstructions. This process usually includes reference to other paleoclimatic records and reconstructions in the region (e.g.,Meko et al., 2007). The Harmon Canyon tree-ring chronology plotted in Fig. 13 (top) corroborates the mid-1100s Colorado River drought in that tree-growth at Harmon Canyon then was lower than at any time from the early A. D. 500s to present. This is independent validation because the Harmon Canyon chronology prior to A.D. 1183 was not used in the streamflow reconstruction itself (Meko et al., 2007). An early A.D. 500s low in growth at Harmon Canyon is intriguing (Fig. 13 , top), but without data from other parts of the Colorado River basin cannot yet be interpreted as evidence of basin-wide drought.

8. Conclusion

Robust and accurate estimates of the magnitude and duration of severe hydrologic droughts is an important contribution of dendrochronology to hydrology and water-resources management.

Analysis of a persistent reconstructed drought in the mid-1100s on the Colorado River illustrates both the type of information tree-ring analysis can provide, and the challenges to interpretation. The 1100s drought is a rare event in that no similarly low 25-yr running mean of flow exists in the observed record of natural flows. Time series of simulated flow suggest, however, that given the persistence properties of observed flows we might expect as low a 25-yr mean flow on average about once every 4–6 centuries. Our simulation results are consistent with the mid-1100s drought as a footprint of today's flow variability viewed in an expanded time window. In that sense the magnitude of the mid-1100s tree-ring drought cannot be regarded as remarkable. Impact on multiple large basins in the western United States is an aspect of the 1100s drought that deserves increased attention in hydrologic and climatological studies. On the Colorado alone, the drought is shown using the CRSS model to have devastating potential impact in lowering lake levels.

With the mid-1100s drought we are addressing primarily a low-frequency climatic signal in the tree-ring record. The mid-1100s was in fact not unusual for severity of low flows in individual years, but for the persistence of moderately-dry years and absence of wet years for several decades (Meko et al., 2007). The methods used here can be generalized to the study of higher-frequency features. Higher-frequency fluctuations in runoff can also be important to water resources in the Colorado River basin, and depending on the hydroclimatology, storage, and management practices, may be of primary importance in other basins.

Reducing uncertainty of streamflow reconstruction at all frequency ranges remains a great challenge, especially in the early part of the tree-ring record. The Colorado River reconstruction has a demonstrated signal at multi-decadal wavelengths, but multi-century wavelengths are problematic. Reduced uncertainty for periods more than 800–1000 yr ago is likely to require a combination of improved statistical modeling procedures and — for large basins such as the Colorado — better data coverage by tree rings.

Acknowledgement

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jhydrol.2010.11.041.

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SPECIAL FEATURE

A 1,200-year perspective of 21st century drought in southwestern North America

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A key feature of anticipated 21st century droughts in Southwest North America is the concurrence of elevated temperatures and increased aridity. Instrumental records and paleoclimatic evidence for past prolonged drought in the Southwest that coincide with elevated temperatures can be assessed to provide insights on temperature-drought relations and to develop worst-case scenarios for the future. In particular, during the medieval period, ∼AD 900–1300, the Northern Hemisphere experienced temperatures warmer than all but the most recent decades. Paleoclimatic and model data indicate increased temperatures in western North America of approximately 1 °C over the long-term mean. This was a period of extensive and persistent aridity over western North America. Paleoclimatic evidence suggests drought in the mid-12th century far exceeded the severity, duration, and extent of subsequent droughts. The driest decade of this drought was anomalously warm, though not as warm as the late 20th and early 21st centuries. The convergence of prolonged warming and arid conditions suggests the mid-12th century may serve as a conservative analogue for severe droughts that might occur in the future. The severity, extent, and persistence of the 12th century drought that occurred under natural climate variability, have important implications for water resource management. The causes of past and future drought will not be identical but warm droughts, inferred from paleoclimatic records, demonstrate the plausibility of extensive, severe droughts, provide a long-term perspective on the ongoing drought conditions in the Southwest, and suggest the need for regional sustainability planning for the future.

climate change | water resources | paleoclimatology | medieval period

Climate-change projections clearly indicate what observations already suggest: Temperatures everywhere will be warmer in the future due to anthropogenic activities. General circulation models (GCMs) project continued warming, with annual temperatures 3–5 °C above current levels by the end of the century (1). As previous articles in this Special Feature have discussed, warming temperatures, even without reductions in precipitation, will have far-reaching impacts on hydrologic sustainability in the Southwest. Twenty-first century droughts will occur under warmer temperatures with greater rates of evapotranspiration than occurred during the major droughts of the 20th century. Warming may also directly and indirectly increase the propensity for droughts in the Southwest (2–4). However, major 20th century droughts pale in comparison to droughts documented in paleoclimatic records over the past two millennia (5). Thus, warm droughts of the prehistoric past might provide evidence useful in understanding the current climatological changes, and for providing scenarios for worst-case droughts of the future and evidence of hydroclimatic responses in the Southwest to warmer climatic conditions.

This paper examines recent temperature-drought relations and analyzes paleoclimatic data documenting droughts persisting for periods of a decade or more, develops evidence for drought linkages with elevated temperatures, and identifies “worst-case” scenarios for warm-climate drought to place the recent episode of drought in the Southwest in a long-term context. As the current early 21st century drought has occurred with elevated temperatures, warm-period paleo droughts may well be a preview of what can be expected for the future. The recent prolonged drought has already had significant impacts in the arid to semiarid Southwest. Currently, overallocated water resources are being further stressed by increased demands due to population growth, tribal settlements, changes in land use, recreation needs, and mandated requirements for instream flows for ecosystem functioning and endangered-species preservation (6–9). As a result, many water-supply systems have become increasingly vulnerable to drought impacts. The recent drought has underscored the critical need for sustainable water-resource management and development (10). Such strategies should be informed by as long and complete a record of drought behavior and impacts as possible.

Warm Droughts in the Southwest: Past Droughts as Analogues for the Future?

The Role of Temperature. Elevated temperatures can have direct, local effects on drought as well as impacts on circulation features that promote large-scale droughts. Southwestern droughts are, typically, accompanied by above average temperatures because of factors such as subsidence, a lack of cloud cover, drying soils, and reduced evapotranspiration (e.g., 11–13). Major 20th century droughts, including the 1930s and 1950s, have occurred during periods of elevated temperatures, with persistence of high pressure leading to surface heating and drying in both winter and summer (11, 14, 15) (Fig. 1) and storm tracks displaced around the drought region (16). However, droughts do not always coincide with above average temperatures (17), as exemplified in the U.S. Southwest by the drought at the start of the 20th century (Fig. 1).

Global or hemispheric warming may also strongly impact Southwest drought indirectly through influences on global sea surface temperatures (SSTs) and ocean/atmosphere dynamics. Increased radiative heating over the tropical Pacific has been shown to enhance the development of La Niña-like conditions that promote drought in the Southwest (4, 5, 18). It has been suggested that the influence of global warming on the western tropical Pacific and Indian Oceans may already be detectable, and along with cool SSTs in the eastern tropical Pacific, may have been a cause of drought conditions at the turn of the 21st century that affected regions including southwestern North America (19). One projected (and possibly already detected) result of global warming is an extension of the poleward arm of the Hadley cell that will cause an expansion of the area under the drying

SUSTAINABILITY SCIENCE

Author contributions: C.A.W., D.M., G.M.M., D.W.S., and E.C. analyzed data; D.M., G.M.M., D.W.S., and E.C. contributed new reagents/analytic tools; and C.A.W., D.M., G.M.M., D.W.S., and E.C. wrote the paper.

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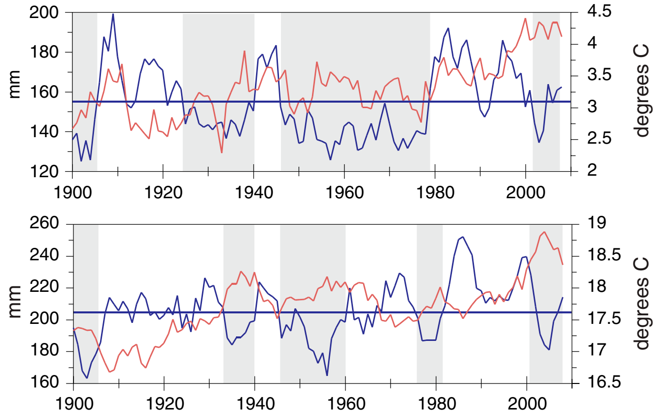

Fig. 1. Total seasonal precipitation and mean seasonal temperature averaged over Colorado, Utah, New Mexico, and Arizona (17); five-year running means, 1900–2008. Precipitation in *Blue Line* (*Horizontal Line* is the average), temperature in *Brown*. Cool season (November–March), *Top*. Warm season (May–October), *Bottom*. *Shading* indicates periods of below average precipitation.

influence of subtropical high pressure (2, 20). Whereas some of these large-scale responses to warming may not have operated in the past others, such as SSTs anomalies in the tropical oceans, have been critical drivers. Past droughts best suited as analogues for the future are those accompanied by hemispherical temperature changes favoring drought-inducing circulation and directly amplifying regional drought conditions and impacts.

Warm Paleodrought. Paleoclimatic data for southwestern North America provide extensive documentation of past droughts (21, 22). Records collectively suggest a broader range of hydroclimatic variability than contained in instrumental records, particularly with respect to drought extent, duration, and severity. Several notable droughts extended across much of western North America, including severe and sustained droughts in the late 16th century and the medieval period, between 900–1300 AD (23–25). In this period, episodes of extensive severe drought are documented by a variety of proxy data, but most dramatically by evidence of trees rooted in lakes and river courses in the Sierra Nevada and northwestern Great Basin (26, 27). These droughts appear to have exceeded the duration and magnitude of any subsequent droughts in western North America (5, 25).

Whereas the medieval period is now acknowledged as a time of increased aridity over western North America, it has more generally been known as a period of warmer temperatures, especially over Europe (28, 29). An effort has been made to document the degree to which global and hemispheric temperatures were elevated at this time using a wide variety of proxy records, and with an emphasis on understanding the low-frequency component of variability (1, 30, 31). A recent analysis of a number of different proxy temperature records suggests that Northern Hemisphere decadal-scale averages over land may have been as much as approximately 0.2–0.4 °C above the 1850–2006 mean from roughly 950–1150 AD (32). The medieval warming is, however, markedly exceeded by late 20th and early 21st century warming, as temperatures now stand more than 0.8 °C above the 1850–2006 mean (32).

Ocean/atmosphere teleconnections provide a plausible causative link between hemispheric-scale warm temperatures and drought in the Southwest during the medieval period. Associations between SSTs and Southwestern drought during this period have been explored with paleoclimatic data and modeling (4, 33–35) and although the paleoclimatic data that document Pacific Ocean conditions during the medieval period are not in total agreement, most show temperatures in the eastern Pacific indicative of cool El Niño/Southern Oscillation, or La Niña-type conditions (22). More unequivocal evidence exists for a warm North Atlantic (36). Recent modeling efforts, assuming cool Pacific and warm Atlantic SSTS, have replicated the main features of medieval drought in North America documented in paleoclimatic data (36). It is worth noting that droughts of the 1950s and of recent years were both accompanied by cool Pacific and warm Atlantic SSTs (37).

Although likely not matching the magnitude of the recent increases in global temperatures, the increased large-scale hemispheric warming in medieval times coincided with widespread and persistent aridity across the Southwest. On a regional scale, paleoclimatic data indicate that similar to the instrumental period, warm and dry spells often concur in the Southwest, including during this period (13). Is it appropriate then to consider a medieval drought as a possible, although conservative (with respect to temperature), analogue for future warm droughts? The root causes of warming for the medieval period, increased solar irradiance coupled with decreased volcanic activity (38, 39), and in recent decades, anthropogenic activities with some contribution from solar irradiance (1), are not identical. Although important differences must be acknowledged—for example, the causes and the amplitudes of the warming, and the probable impacts of land cover change on temperatures—the medieval droughts can provide some direct evidence of the Southwest hydroclimatic response to warming and a plausible, but conservative, worst-case scenario to be considered in sustainable water-resource planning.

Medieval Drought and Temperatures in Southwestern North America

The medieval period was characterized by widespread and regionally severe, sustained drought in western North America. Proxy data documenting drought indicate centuries-long periods of increased aridity across the central and western U.S. (Fig 2*F*) (25, 22). In the Colorado and Sacramento River basins, reconstructions show decadal periods of persistently below average flows during several intervals including much of the 9th, 12th, and 13th centuries (40–42) (Fig 2*E*). The 12th century episode, also reflected in precipitation and drought extent (13, 25, 43, 44), was particularly severe and persistent and was associated with a peak in solar irradiance and nadir in volcanic activity (4) (Fig. 2*A*). Most of these paleohydrological records primarily reflect winter and spring precipitation. Proxy records that document summer precipitation are much less common and, of those that do exist, some suggest wetter summers during the medieval period (22, 45–47), whereas others indicate decadal variability of both drought and wetness (48).

The temperature signal of the medieval period, though relatively strong in averages over the Northern Hemisphere (32) (Fig. 2*B*), is more complex at the regional scale (29). In contrast to paleohydrological records, there are fewer high-resolution paleotemperature records in the Southwest and evidence for anomalous medieval warmth in this region is less comprehensive (5). Tree-ring reconstructions of temperature for the Southwest suggest warmer temperatures for at least portions of the medieval period (13, 29, 49–51). These reconstructions usually represent growing-season temperatures and, because of limitations of the paleoclimatic indicators generally do not preserve centennial-scale variations (52, 53), at least on these regional scales. Along with evidence for multiyear periods of enhanced temperatures approaching 1.0 °C during some intervals of the medieval period, records also indicate periods of normal to below average temperatures at other intervals (Figure 2*D*). Proxy records are consistent, however, in supporting periods of elevated warmth in the medieval period that coincide with periods of severe and widespread drought.

At multidecadal and longer timescales, evidence from treeline, glacier, and chironomid studies suggests southwestern North

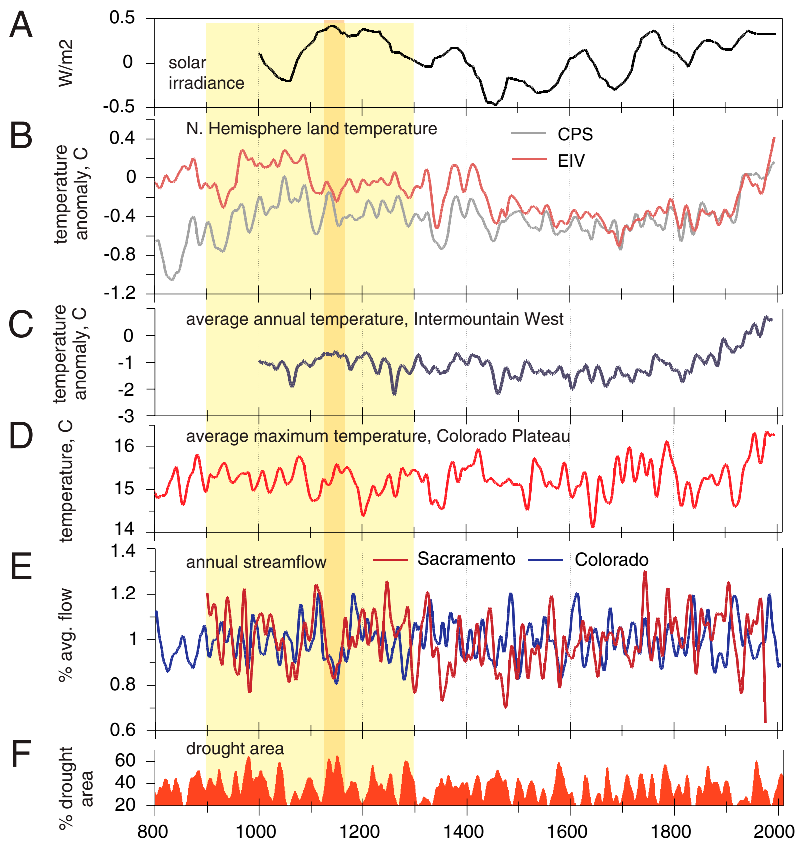

Fig. 2. Global, hemispheric, and regional proxy and model data documenting medieval period conditions. *A* Solar irradiance (69), *B* two estimates of Northern Hemisphere land temperatures, departures from 1850–1995 (32), *C* ECHO-G (60) modeled average annual temperature for 34°–40° N, 104°–124° W, and departures from 1890–1990, *D* reconstructed Colorado Plateau mean maximum temperatures (13), *E* reconstructed water year streamflow, Colorado River at Lees Ferry (41) and Sacramento Four Rivers index flow (40), percent of average based on AD 901–1977, and *F* reconstructed Southwest Drought Area Index (5). All series except (*A*) were smoothed with a 20-year spline. *Light Shading* indicates medieval period, *Dark Shading* indicates mid-1100s period.

America and adjacent regions experienced elevated temperatures on the order of 1 °C or less above long-term means during some or all of the medieval period (refs. 54–58). Medieval warming in western North America is also suggested by climate model simulations from the ECHO-g atmosphere-ocean general circulation model (GCM) (59, 60) that indicates annual temperatures in the region in the 12th and early 13th centuries were about 0.5 °C warmer than the long-term average (Fig. 2*C* and *SI Text*). The medieval period represents the longest episode of elevated temperatures outside of the 20th century, although 20th century temperatures clearly exceed those of the medieval period. Whether decadal-scale warm temperatures in high-resolution proxy records were superimposed on this baseline warming over the medieval period is unclear, but a medieval drought that occurred during a period of decadal-scale warmth could provide evidence for the propensity of hemispheric warming to generate prolonged aridity in the Southwest and a potential scenario for future warm droughts.

Placing the Current 21st Century Drought in a Medieval Context

Worst-Case Medieval Drought. High-resolution proxy data for the Southwest allow an assessment of the intensity, duration, and spatial extent of droughts. Although many proxy records exist, we select a few here to illustrate a worst-case warm drought from the past 1200 yr. One of the longest records of drought intensity and persistence in the Southwest, beginning in the 8th century and ending in the 21st century, is the reconstruction of water-year streamflow for Lees Ferry on the Colorado River (41). This tree-ring based reconstruction summarizes hydroclimatic variability in the most important river basin in the Southwest. Drought extent over the larger domain of the Southwest is documented by an index of drought-area (DAI) reconstructed from a network of moisture-limited tree-ring chronologies (5) (*SI Text*). The Colorado River reconstruction ends in 2005, whereas the DAI ends in 2006 [although from 1979, the data are based on observed Palmer Drought Severity Index (PDSI)]. Several temperature reconstructions exist for the Southwest; the most recent high-resolution reconstruction of temperature was generated by Salzer and Kipfmueller (13) for the southern Colorado Plateau (average annual maximum temperatures), and was used for this analysis (*SI Text*). This reconstruction extends from 663 BC to AD 1996, but is most robust after 266 BC.

Together, the Colorado River flow, Southwest DAI, and southern Colorado Plateau temperature reconstructions allow an assessment of the covariation of hydrologic drought with annual maximum temperatures, AD 762–1996. An analysis of 10-year averages of temperature and streamflow suggests that severe droughts coincide most often with warm temperatures in the medieval period and the 20th century, whereas cool droughts were more common during the pre- and post-medieval periods, before the 20th century (Fig. S1). The warmest, driest, most widespread interval of drought documented in the streamflow, DAI and temperature records occurred in the mid-12th century (Fig. 2 and Fig. S2). The driest 10-year period in the Colorado River reconstruction and the 6th most extensive drought-area in the Southwest was 1146 to 1155. Decades ending in 1153, 1154, 1156, 1157, and 1158 were similarly dry and warm. The decade 1146–1155 ranked in the 80th percentile of southern Colorado

Plateau temperatures. Several decades in the late 9th and 13th centuries were nearly as warm and dry.

Based on these data, the 10-year period, 1146–1155, was selected as a scenario of worst-case warm drought from the paleoclimate data for the past 12 centuries over the Southwest. Over this period, reconstructed Colorado River flows averaged 14.2 billion cubic meters (BCM) per year, the area of the Southwest under drought averaged 65.5%, and average annual maximum temperatures were 15.65 °C. In contrast, the mean annual flow of the Colorado River over the 20th century (1906–2007) has been 18.3 BCM, average area under drought, 32.6% (1900–2006), and average temperature 15.72 °C (1909–2008) (Table S1). Proxy records that better reflect low-frequency temperature variability, such as lake sediments and treeline changes, suggest that warmth was underestimated by the tree-ring reconstructions of annual temperature for the Colorado Plateau. It is possible that, when conditions are dry enough, high elevations conifers do not respond to increased temperatures. As discussed above, climate model results and other types of proxy data suggest medieval temperatures were perhaps 1 °C above the long-term and equivalent to the 1961–1990 mean. The decadal-scale variability reflected in the temperature reconstruction from tree rings may well be superimposed over this warmer baseline, but the warmth still would not likely match the observed average maximum temperatures over the past decade (17.54 °C mean maximum average for 1999–2008, Fort Valley, AZ, Western Regional Climate Center) (Table S1).

In parts of the Southwest with appreciable summer rainfall, any comprehensive assessment of drought—particularly with regard to impacts on society and ecosystems—must also address the North American Monsoon (NAM). The NAM is indeed a key component of drought variability in north-central Mexico, Arizona, and New Mexico, but the paleoclimatic record of summer rainfall over the Southwest is very limited. Currently, one reconstruction reflecting NAM variability has been generated that includes the medieval period (48). This reconstruction of northern New Mexico July precipitation from latewood tree-ring widths is based on data from one location and, thus, may not reflect moisture conditions over the broader domain of the NAM. It does not show an obvious signature of drought in the medieval period, as do the streamflow and DAI records, but there is a multidecadal episode of warm season drought beginning in the 12th century that would have contributed to the overall dry conditions at the time (48).

21st Century Drought in a Long-Term Context. Drought conditions, especially in the cool season, have generally dominated over many parts of southwestern North America since at least 1999 (4, 61) (*SI Text*). Whereas in some parts of the Southwest, and by some measures, the recent drought has not (yet) been the most severe drought in the instrumental period (5, 61, 62), it is notable for warm temperatures (37, 61, 63) (Fig. 1). The combination of precipitation deficits and high temperatures has resulted in hydrologic conditions in some areas that match if not exceed the severity of the 1950s drought (Figs. 3*B* and 4). In addition to the period 2000–2004, which was the lowest five-year period of natural flow on the Colorado River (1906–2005) (64), the most recent decade, 2000–2009, is the lowest 10-year running-mean, followed by ten-year periods ending in 2008 and 2007 (Fig. 4).

The recent drought, thus far, pales hydrologically in comparison to the worst-case drought documented in the medieval period in both spatial extent (Fig. 3) and duration. Spatially, the mid-12th century drought covers all of the western U.S. and northern Mexico except for a small portion of the far northwestern Great Plains, whereas the 21st century drought has not impacted parts of the Pacific Northwest. The 21st century drought has lasted about a decade so far, whereas the 12th century medieval drought persisted with an extent and severity displayed in the worst-case

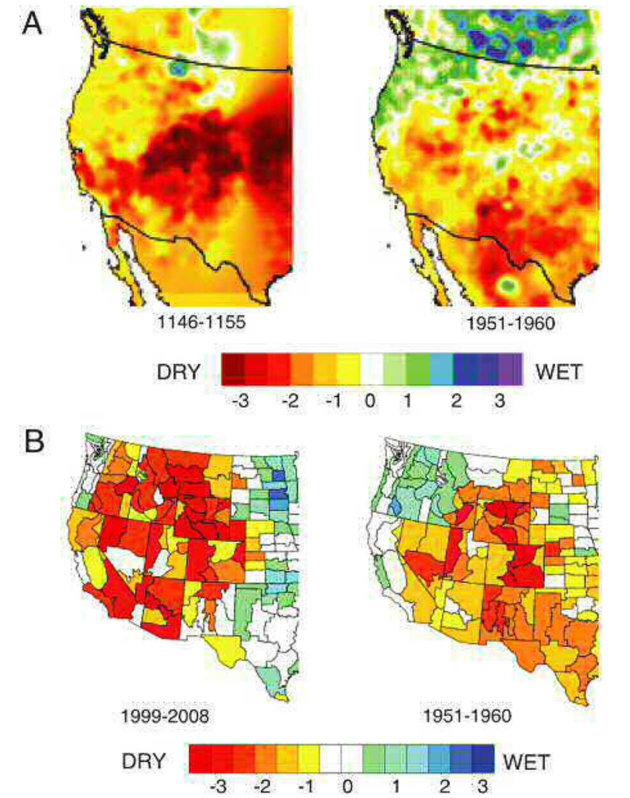

Fig. 3. Composite maps of summer PDSI. *A* Gridded PDSI, reconstructed, *1146–1145*, *Left*; instrumental, *1951–1960*, *Right* (5). *B*. Divisional PDSI, *1999–2008*, *Left*; *1951–1960*, *Right* for comparison with gridded PDSI (70, Image provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site at http://www.psd.noaa.gov/). Note slightly different scales; *Red* indicates dry conditions and *Blue* indicates wet.

decade, 1146–1155, for two decades, 1140–1159. Temperature, on a hemispheric scale, was elevated relative to the past 12 centuries for most of that period. The Colorado River reconstruction also highlights the exceptional persistence of medieval drought. Whereas the maximum number of consecutive years below median flow in the gage record is 5 yr, the long-term reconstruction contains a total of 17 longer runs. The longest is 13 yr in the mid-1100s, a period characterized by stretches of moderately low flows and lack of high flows (41). Whereas individual annual reconstructed flows were not exceptionally low in the mid-1100s, a lack of wet years translates into record-low averages over periods

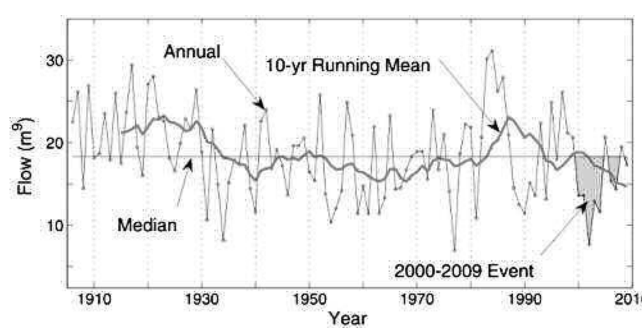

Fig. 4. Observed annual flow of the Colorado River at Lees Ferry. *Horizontal Line* is the median of the 1906–2006 observed flows (18.32 billion cubic meters). *Light Gray* line is the 10-year running average. Observed flows are version 6.18.08 of the natural flows from the U.S. Bureau of Reclamation (http://www.usbr.gov/lc/riverops.html), appended with provisional flows for water years 2007–09 that were estimated by the Bureau of Reclamation with data currently available.

of a few decades. The 10-year running-mean of reconstructed flow drops below the observed 2000–2009 mean (14.65 BCM) only four times in the entire reconstruction, and three of those are in the mid-1100s. Because regression-based tree-ring reconstructions tend to be conservative, this evidence strongly suggests the mid-1100s were at least as dry as the last 10 yr. In reconstructed Sacramento River streamflow, the 20-year period ending in 1158 was the second driest in this record that extends to AD 869 (40), indicating the impact of this drought in northern Sierra Nevada watersheds as well. However, one critical drought-related variable, temperature, was almost certainly higher during the 21st century drought than during the medieval droughts.

Summary and Conclusions

In both instrumental and paleoclimatic records, periods of sustained drought in the Southwest have often been concurrent with elevated temperatures. The warmest such episode, in the mid-12th century, was more extensive and much more persistent than any modern drought experienced to date, with cumulative streamflow deficits on the Colorado and Sacramento that would severely tax the ability of water providers to meet demands throughout the Southwest. However, temperature, an important feature of that drought, was very likely lower than in the recent period of drought. It should be noted that records of past temperature for the Southwest are still limited, and this assessment would be strengthened with additional paleoclimatic data for this region. Studies assessing the impact of elevated temperatures on Colorado River runoff indicate that warming will lead to intensified low flows and a greater probability of water shortages (65—67). A wide variety of modeling efforts have yielded results that suggest, for each 1 °C increase in temperature, runoff will decrease from 2–8% in the Colorado River basin (67). The medieval drought conditions documented by tree rings are biased towards the cool season, the most important season for water supply in much of the Southwest. While monsoon season moisture may increase with global warming, this would not be likely to offset winter drying in most regions.

Warming temperatures will likely further exacerbate drought in the Southwest in ways both with and without analogue in the past. The enhancement of the ocean/atmospheric circulation features that promote the establishment and persistence of drought in this region is a main driver of drought in the past. Paleoclimatic data can provide insights on the associated regional drought responses. The expansion of the region dominated by subtropical high pressure, an anthropogenic influence on drought extent (2), will need to be considered on top of naturally occurring forcings in the anticipation of future droughts.

As far as we know, there is no reason why droughts of the duration, severity, and spatial extent experienced in the medieval period could not occur in the future. Even without the anticipated increased warming in the 21st century, droughts of the magnitude of the medieval droughts would present enormous challenges to water management agencies. Worst-case droughts of the 20th century, unlike those of the paleo record, do not contain episodes of many consecutive decades without high flows, so critical for refilling of reservoirs (41). The large spatial extent of medieval droughts would also present management challenges, particularly in areas such as southern California, which relies on water supplies from both the Colorado River and Northern Sierra watersheds.

Although these "warm" medieval droughts may be considered conservative analogues for future droughts, it is important to recognize that there are many reasons that the mid-12th century drought cannot be considered an exact analogue for future worst-case droughts. Besides anthropogenic warming, there have been a multitude of changes in land cover throughout the Southwest due to human activities since the late 19th century. Conversion of desert and grassland to cropland, grazing, fire suppression, introduction of invasive species, disturbances leading to soil erosion and blowing dust, and the development of urban areas have all likely had impacts on regional climate. No systematic studies on these land cover changes and their impacts on climate or drought have been undertaken (68), but these changes are another important reason that droughts of the past are unlikely to be an exact analogue for current and future droughts. In addition, from an impacts standpoint, droughts have a much broader range of impacts on human activities today than in the past because of today's greater demands on limited water resources.

Analogues can provide a basis for planning, but realistic and plausible future scenarios must consider a host of other factors. The paleoclimatic record is invaluable for documenting the range of drought variability over the past and expanding the scope of worst-case scenarios. The mid-12th century drought provides a baseline worst-case in terms of the temporal and spatial characteristics of drought during a warm period, but future water resources and drought planning should consider a number of other factors including trends in temperature, water demands, disturbance legacies, and possible land cover feedbacks. The baseline worst-case is clearly just a starting point in planning for droughts that will be further exacerbated by these other factors. The challenge of dealing with such droughts argues strongly for innovative strategies for sustainable water management under a warmer, drier climate.

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