# ~Enhancing Water Supply Reliability~

## An Interdisciplinary Research Project to Enhance Predictive Capacity on the Colorado River

Final Report Phase I
November 2006

Photos of Lake Powell at the confluence of the Dirty Devil and Colorado Rivers trace the reservoir's rapid depletion from June 2002 (top) to March 2003 (bottom). Five consecutive years of drought from 1999 to 2004 have underscored water supply reliability challenges in the Colorado River Basin (Photos: John Dohrenwend, USGS).

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**ON BEHALF OF BONNIE COLBY, BART NIJSSEN[2], DAVE MEKO,**
**AND PETER TROCH[3], UNIVERSITY OF ARIZONA**

**DATE:** **NOVEMBER 7 , 2006**

**RE:** **FINAL REPORT, PHASE I**
**ENHANCING WATER SUPPLY RELIABILITY PROJECT**

The enclosed materials constitute the final report for Phase I of the University of Arizona – U.S. Bureau of Reclamation report on Enhancing Water Supply Reliability Through Enhanced Use of Climate Information. We are very pleased that Reclamation has chosen to continue this project for another two years. Our collaboration has proven fruitful from a number of perspectives, including development of an interdisciplinary team focused on new ways to use climate information in managing the Lower Colorado River and contributions to the education of 6 graduate students (to date). Although our approach has been experimental, in many regards our expectations have been exceeded – in terms of the support we have received from stakeholders because of our focus on responding to their specific questions, the number and quality of products that have been developed, and the very positive ongoing relationships between Reclamation staff and the University of Arizona faculty and students.

Phase I of our project included: a) assessing current Bureau of Reclamation use of climate information in river modeling; b) identifying strategies to better utilize paleoclimatology, climate forecasts and climate change predictions to improve water supply predictive capacity for the lower Colorado River and the Central Arizona Project; c) evaluating existing state and federal management tools to translate improved predictive capacity into enhanced supply reliability for water users and d) developing practical supply reliability strategies for use water users and managers at various scales.

[2] Bart Nijssen is no longer a faculty member at the UA, he is a private consultant in Seattle
[3] Peter Troch has joined this project as the Hydrology team leader as of August, 2006; Andrew Wood of the University of Washington will be providing hydrologic modeling services and climate data through a subcontract

More specifically, we have demonstrated the application of downscaled climate information through a hydrology model to generate flows that can be used in the 24-month operations model for managing the Lower Colorado as an initial demonstration of how seasonal climate predictions and longer term climate change information could be incorporated into Reclamation models; extended the tree ring record for portions of the watershed and completed reanalysis of flow reconstructions based on dendrochronology, with a focus on enhancing the utility of these data for understanding past and possible future water supply conditions; completed a review of dry-year strategies for responding to droughts of various durations and intensities, and worked with stakeholders to focus our research on issues of concern to them, particularly relative to modeling uncertainties and development of shortage criteria.

The deliverables of this project include an email newsletter that is circulated quarterly to a list of over 350 interested parties. Each newsletter contains an update on the drought status in the Colorado basin, recent research results, and articles that respond to questions that we were asked by stakeholders. This has proven to be a very effective way to communicate with stakeholders and emphasizes Reclamation's commitment to an open process relative to the development of shortage criteria. We have also created a project website, and the majority of our products are linked to this site: http://ag.arizona.edu/AZWATER/EWSR/

## PHASE II SCOPE OF WORK

Phase II of this project involves further development of our research partnership, including the Arizona Water Institute, a collaboration of the 400 faculty members at Arizona's three universities. Phase II started with a stakeholder workshop to review the results from Phase I and discuss potential future directions on September 6, 2006. The work over the next two years will include demonstrating additional strategies for enhanced use of climate information in Bureau of Reclamation river system modeling and river operations. The general ideas being considered include a) demonstrating how tree ring-generated flow information can be used in modeling activities, b) demonstrating the use of downscaled global circulation model forecasts and climate change predictions to improve predictive capacity/reduce system vulnerability for the Colorado River system broadly, c) focusing on predictive capacity in subwatersheds within the Lower Basin, where the ENSO signal is strongest; d) evaluating specific management tools designed to translate improved predictive capacity into enhanced supply reliability for water users, including tools that can be used by federal and state agencies, municipalities, irrigation districts, tribes and other stakeholders; and e) engaging with other research groups and key stakeholders to tailor research foci, approach and findings for applications of interest to Reclamation. In this vein, we intend to convene a workshop that is focused on developing a research agenda for enhancing climate predictions in the 1-3 year time frame.

In our stakeholder workshop on September 6, a number of suggestions were made regarding potential directions for our Phase II activities. As our scope of work is relatively general, there is potential to focus on specific research questions within our framework.

Areas of particular note from the September 6 meeting include:

Hydrology/Tree Ring Suggestions

- The potential to develop ensembles that illustrate the impacts of different management options, since predictions of water levels in the reservoirs result from a combination of inflows and decisions about how much water to release
- Identify different frequency-modes of streamflow variation over several centuries, with possible explanations
- Reconstruct discharge of the Little Colorado River near Cameron as a pilot study for incorporating tree-ring data into CRSS
- Develop a suite of tree-ring streamflow reconstructions to use as inputs at multiple nodes of the CRSS and the 24 month study models
- Collaborate with BoR researchers to disaggregate tree-ring reconstructed flows into monthly flow estimates suitable for input into the CRSS model
- Evaluate the use of alternative (non-linear) reconstruction models for small, semi-arid sub-basins with flashy flow regimes
- Provide advice on how to determine if recent observed variations in flow are anomalous in the context of long-term natural climate variability
- How to link the long-term model to climate change models

- Linkage to increased groundwater pumping and ecological impacts related to river flows away from the mainstem

Dry Year Option/Response Strategy Suggestions

- Evaluate new ways to address third party impacts from water leases and dry year options, using a rebuttable presumption with a burden of proof of what the impacts are
- Develop risk adjusted measures of net farm returns
- Evaluate long term vs short term third party impacts over periods of time
- Demonstrate alternative applications of dry year options for different climate predictions (eg long term vs short term drought), distributions of costs and benefits, implications of changes in farm bills, and effects on farm profitability
- Look at Met and Palo Verde as examples of exchanges to evaluate

Water Management Strategy Suggestions

- Assist in framing shortage sharing discussions with stakeholders
- Evaluate intentionally created surplus implementation options
- Identify lead times to get dry year option agreements in place, what preparations are needed, trigger mechanisms
- Issues within the Phoenix metro area for implementation of options. What about between US and Mexico? Are there international applications?
- How to evaluate the shortage alternatives in the context of climate change
- Stakeholder engagement piece is critical, wants to be transparent
- Expose areas of uncertainty
- For CAP one of the biggest wildcards is the onriver use over the next 50 years, need to identify trends and scenarios for onriver use
- Tribal water development on river, currently using half of entitlement
- Range of climate variation, linked to timing and response options
- "The 800 lb gorilla is that we overallocated the river, need to use this project as the beginning of the discussion about how to change the institutions."

Potential New Foci Resulting from Peter Troch's Participation

- Coupled atmosphere river basin water balance, including measurements of groundwater storage using GRACE satellite data
- Explain variability through multiple oscillations, gravity, etc. to increase understanding of fluctuations and reduce uncertainty

We are interested in your feedback regarding prioritizing these ideas.

The past few months have been spent finalizing our Phase I products and focusing on resolving all of the administrative and budget issues that are associated with moving forward. We anticipate that our next newsletter will be available for review in December. Please let us

know if you have any specific questions or comments regarding this memo or any of our products.

Thank you for the opportunity to work on a project that has such relevance and potential impact. We appreciate your support, both financial and personal.

**PROJECT DELIVERABLES**
**PUBLICATIONS AND PRESENTATIONS AS OF 10/15/06**

View http://ag.arizona.edu/azwater/ewsr to access online versions of all available publications, presentations, and media coverage of project results.

Publications include links if on our website

Six editions of "Enhancing Supply Reliability" Project Newsletter

Colby, B., K. Pittenger, and L. Jones. "Voluntary Irrigation Forbearance to Mitigate Drought Impacts: Economic Considerations." Technical Report (October 6, 2006)

Colby, B. and K. Pittenger. "Temporary Water Transfers in the West: An Econometric Analysis." Draft manuscript in preparation for journal submission.

Colby, B. and K. Pittenger. "A Farm Budget Approach to Valuing Irrigation Water in Western Arizona and its Application in Structuring Temporary Water Transfers." Draft manuscript in preparation for journal submission.

Garrick D and K Jacobs. "Tree Ring Records Inform Water Management Decisions." *Southwest Climate Outlook*. Climate Assessment for the Southwest. May 2005

Garrick D and K Jacobs. "From Surplus to Shortage in the Colorado River Basin." *Southwest Hydrology*. V3. Issue 5: May/June 2006.

Garrick, D, K Jacobs, and G Garfin (in review). "Decision Making under Uncertainty: Shortage, Stakeholders, and Modeling in the Lower Colorado River Basin." *Journal of American Water Resources Association*. Submitted March 2006.

Lindenmayer, L. Evaluating Experimental Streamflow Forecasts for Use in Reservoir Modeling in the Colorado River basin. Master's Thesis. (September, 2006).

Meko D. M. and Woodhouse C. A. (in review) Dendroclimatology, dendrohydrology, and water resources management. In Dendroclimatology: progress and prospects (ed M. K. Hughes, T. W. Swetnam and H. F. Diaz)

Pittenger K and B Colby. "Structuring Voluntary Dry-Year Transfers." Conference Proceedings. *50th Annual New Mexico Water Conference*. WRRI Report No. 339. (Spring 2006).

Pittenger, K. "Economic Arrangements to Enhance Dry Year Supply Reliability in the Lower Colorado River Basin." Master's Thesis. (June 2006).

St. George, S. Applying long-term streamflow and paleohydrological data to inform decisions on water management [Abstract]. Climate Change and Hydropower Workshop. Winnipeg, Canada, March 2 – 3, 2006.

Woodhouse C. A., Gray S. T. and Meko D. M. Updated streamflow reconstructions for the Upper Colorado River Basin. *Water Resources Research* 42, W05415, doi:10.1029/2005WR004455. (May 2006)

## Presentations

Team Presentations to Reclamation staff: August 24, 2004; August 17, 2005; March 14, 2006; September 6, 2006. Final workshop presentations available online at http://ag.arizona.edu/azwater/ewsr.

Colby, B. "Water Shortage Sharing Agreements: An Application for Climate Prediction." Presentation. *4th Annual NOAA Climate Prediction Application Science Workshop*. Tucson, AZ (March 2006).

Colby, B. "Water Shortage Sharing Agreements: The Role of Climate Indicators." Presentation. *2006 UCOWR/NIWR Annual Conference Increasing Freshwater Supplies.* Santa Fe, NM (July 2006).

Garrick, D., K. Jacobs, and G. Garfin. "Decision Making under Uncertainty: Shortage, Stakeholders, and Modeling in the Lower Colorado River Basin." Presentation. *4th Annual NOAA Climate Prediction Application Science Workshop*. Tucson, AZ (March 2006).

Garrick, D. and K. Jacobs. Enhancing water supply reliability: an interdisciplinary research project to enhance predictive capacity on the Colorado River: project overview. Presentation to Colorado River Hydrology Work Group, U.S. Bureau of Reclamation, CADSWES, Boulder, CO, May 2, 2006.

Garrick, D., K. Jacobs, and G. Garfin. "Decision Making under Uncertainty: Shortage, Stakeholders, and Modeling in the Lower Colorado River Basin." Presentation. *Annual Meeting of the Arizona Hydrological Society.* (September 2006)

Jacobs, K., B.Colby, D. Meko, and B. Nijssen, Enhanced Water Supply Reliability Through Improved Predictive Capacity and Response, Water Forum, University of Arizona. November 2005.

Jacobs, K., B.Colby, D. Meko, and B. Nijssen, Enhanced Water Supply Reliability Through Improved Predictive Capacity and Response, AGU 2005 Fall Meeting, December 7, 2005. San Francisco. #H32B-06.

Meko D. M. 2005a. Stationarity and the reconstruction of streamflow from tree rings. Presentation at: Planning Workshop to Develop Hydroclimatic Reconstructions for Decision Support in the Colorado River Basin, May 4-5, 2005, Tucson, AZ.

Meko D.M. 2005b. Tree-ring reconstructions of natural flow at Lees Ferry. Presentation at: Planning Workshop to Develop Hydroclimatic Reconstructions for Decision Support in the Colorado River Basin, May 4-5, 2005, Tucson, AZ.

Meko D. M. and Caprio A. C. 2005. Tree-Ring inferences on spatial coherence of precipitation in the southwestern USA on the millennial time scale. Presentation at the 2005 Geological Society of America Annual Meeting, 16-19 October, Salt Lake City, UT.

Meko D. M. and St. George, S. 2006a. Enhancing water supply reliability: an interdisciplinary research project to enhance predictive capacity on the Colorado River: update on tree-ring component. Presentation to Colorado River Hydrology Work Group, U.S. Bureau of Reclamation, CADSWES, Boulder, CO, May 2, 2006.

Meko D. M. and St. George, S. 2006b. Streamflow records extended with tree rings. Presentation to Lower Colorado River Tour, April 6, 2006 (tour sponsored by the Water Education Foundation).

Meko D. M. 2006a. Tree-Ring Applications to Drought Analysis in the monsoon region. Presentation at Monsoon Region Climate Applications, a Binational Workshop, May 8-11, 2006, Instituto Tecnológico de Sonora (ITSON), Guaymas, Sonora, Mexico.

## Media Coverage

Boxwell, B. "Severe drought traced along the Colorado River." *Los Angeles Times.* Printed May 27, 2006.

"River streamflow reconstructed to 1490." United Press International – USA. Printed May 25, 2006.

"Historic Colorado River Streamflows Reconstructed Back to 1490." University of Arizona Communications. Published May 25, 2006.

Swedlund, E. "UA tree-ring study could affect use of Colorado river water." Arizona Daily Star. Published May 29, 2006.

Versions of this article have been reprinted in several newspapers.

Six (6) editions of stakeholder newsletter, entitled "Enhancing Water Supply Reliability: Improving Predictive Capacity in the Lower Colorado River Basin." Available at: http://ag.arizona.edu/azwater/ewsr

# Summary of Stakeholder Questions

Over 100 questions and comments resulted from the stakeholder meetings between the UA research team and water managers and user groups during Fall 2004. The format of these meetings usually involved a brief presentation of the project scope by the UA researchers followed by a question and answer session. The stakeholder engagement process produced a group of questions that reveals several of the key uncertainties confronting water managers. In addition to guiding efforts by the UA research team, the process has defined a broad agenda for research that will ultimately exceed the scope of this project.

The quarterly newsletter includes articles that respond to several of the questions. The brief summary of the questions that follows is sorted by disciplinary categories, recognizing that answers to these questions will frequently require interdisciplinary approaches.

This key indicates the action being taken to address the stakeholder questions listed below:
**(N)** – Will be addressed in future newsletter
**(R)** – Will be addressed during project as part of research findings
**(F)** – Will guide future research agenda and is beyond the scope of this project

**Climate and Hydrologic Modeling**

* How can a hydrological or climate model be validated? With what level of certainty? Need to include level of confidence as part of findings. **(N)**
* Need to explain difference between stochastic, general circulation, and serial correlation models. **(N)**
* How can models and correlations be translated into a predictive tool? **(N)**
* How much less (or more) runoff does the Colorado River basin receive with 1 degree change in temperature due to soil moisture and evaporative losses? What are the associated changes in agricultural needs? **(N)**
* Is there an opportunity to resample historical data to force worst case conditions? **(N)**
* How much CAP water will be available, and how much do we need to store for future municipal reliability? **(R)**
* Is there a necessary connection between climate change and runoff? What is the relationship between precipitation and temperature changes to vegetation types? **(R/N)**
* Can tree-ring records be used as an input to the Colorado River Simulation System (CRSS)? **(R)**

**Paleohydrologic Record and Tree-Ring Data**

* Seek ways to predict correlations in patterns of runoff trends. For example, are 5 years of high runoff usually followed by 5 low runoff years? (seeking drought/surplus forecasting)? **(N)**
* How reliable are the assumptions of unregulated flow? How much error exists in the naturalized flow projections? **(R)**
* How sensitive are tree rings to low vs. high runoff (can they capture full range of high flow years) ?**(N)**
* Seek mechanism to identify management thresholds (reservoir levels, inflows) for shortage, normal, surplus condition. **(R/F)**
* How long have low-flow periods persisted in the past? **(N)**
* Can tree rings provide information for critical gauge records other than Lees Ferry? Are flows in smaller basins controlled by the same or different climate factors? **(N/R)**
* Stochastic tools give a broader range of expectations, but how do they address issues of "where do we go from here?" in terms of policy decisions? **(R)**

**Water Resource Economic and Policy Impacts**

* What is a dry year option? What are the different types of dry year options available for water managers? **(N)**
* What is the role of agriculture as a water supply buffer during future droughts? What is the total benefit/cost to society? **(F)**

* Can we identify groups of users who have drought supply needs to facilitate the analysis, rather than focusing on multiple water providers? **(R)**
* Can we have a more efficient learning process by evaluating the experience of other states? **(N)**
* What are some of the general implications of diminished hydropower production due to drought? Would higher electricity costs affect groundwater pumping? **(F)**
* What are some of the trade offs confronted in water transfers from agricultural to municipal and industrial uses? **(R)**
* How can water supply options be matched to different drought scenarios, including consideration of the depth, length and amount of warning prior to onset? **(R)**

**Project Management and Water Policy**

* Need to bracket and communicate uncertainty (concern with possibility of having an ambivalent forecast that predicts both shortage and surplus in the same year) **(R)**
* What are the basic assumptions in the CRSS (i.e. Upper Basin use)? How sensitive are these assumptions to climatic and hydrologic variability? **(N/R)**
* How can we make people more comfortable using probabilistic information? **(R)**
* How can we manage public perception concerning blips of high water years during prolonged drought? How do we provide public information in the context of variability? **(N)**
* How can an evolving understanding of climate variables factor into AMA and statewide management plans and projections? **(R)**

# Enhancing Water Supply Reliability

## An Interdisciplinary Project to Improve Predictive Capacity in the Colorado River Basin

Dustin Garrick[1,5], Laura Lindenmayer[2], Katie Pittenger[3], Scott St. George[4], Bonnie Colby[3], Kathy Jacobs[6], Dave Meko[4] , Bart Nijssen[2], Peter Troch[2]

Geography and Regional Development[1], Hydrology and Water Resources[2], Agricultural and Resource Economics[3], Laboratory of Tree Ring Research[4], and Water Resources Research Center[5] at the University of Arizona; Arizona Water Institute[6]

For more project info, visit http://ag.arizona.edu/AZWATER/EWSR



## Background

This interdisciplinary two-year project examines the use of climate information in the management of the Colorado River.

**Figure 1.** *Photos of Lake Powell at the confluence of the Dirty Devil and Colorado Rivers trace the reservoir's rapid depletion from June 2002 (top) to March 2003 (bottom). Five consecutive years of drought from 1999 to 2004 have underscored water supply reliability challenges in the Colorado River Basin (Photos: John Dohrenwend, USGS).*

The project addresses four primary objectives:

**Assess** current Bureau of Reclamation use of climate information in water resources modeling

**Identify** strategies to utilize climatic information and forecasts to improve water supply predictive capacity for the lower Colorado River Basin

**Evaluate** existing management tools to translate improved predictive capacity into enhanced supply reliability for water users

**Develop** practical supply reliability strategies for use by municipalities, irrigation districts and other stakeholders

## Modeling: How can Climate Models help predict streamflow in the Colorado River system?

The **modeling component** of this project has focused on incorporating climate data into current water resource planning methods in the Colorado River Basin. The U.S. Bureau of Reclamation presently uses its 24-month Study model for two-year user and operations planning on the Colorado River. This model is implemented in RiverWare, a software package specifically tailored to water resources management applications. The 24-month Study does not make use of medium- to long-range weather forecasts, nor does it use information about projected future climate conditions. Instead, historical time series of inflows are resampled and averaged together to predict upcoming streamflow scenarios along the river system.

**Findings**

Our project has developed a methodology for incorporating climate information into a water resource management model (Fig. 2). Historically observed precipitation and temperature data from 1950-2001 have been input to a hydrologic model. These meteorological conditions have produced 52 streamflow scenarios based on the past conditions. Each scenario was run through the 24-month Study model to result in 52 different scenarios of inflows and elevations for Lake Mead. The ensemble spread produced was then broken down into different percentiles and compared with USBR predictions and actual conditions. This methodological advance could lead to other climate data being incorporated into USBR river system modeling efforts. These new climate data sources could aid efforts to evaluate the water supply impacts of climate change scenarios by using the outputs from general circulation models as inputs into the RiverWare suite of models.

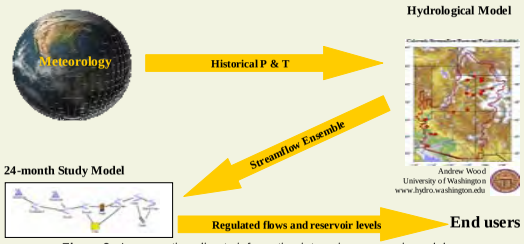
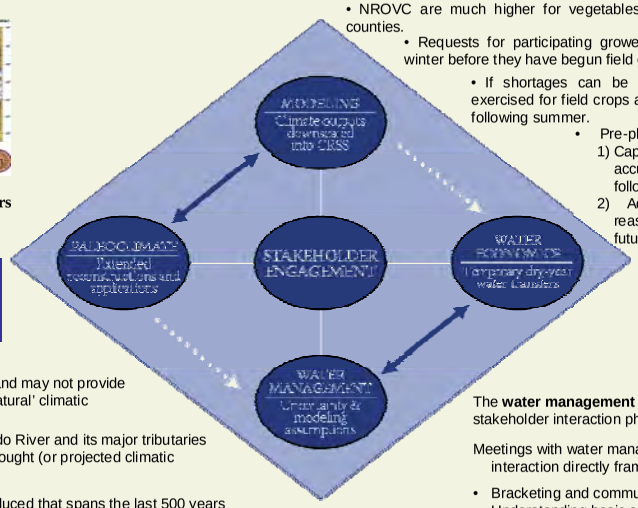



**Figure 2**. *Incorporating climate information into a river reservoir model.*




## Paleoclimatology: How can tree rings aid water managers?

Flow records for rivers in the Colorado River basin cover only the 20th century, and may not provide accurate estimates of the frequency or severity of system-wide drought under 'natural' climatic conditions.

This component of the project used tree-ring data to understand how the Colorado River and its major tributaries have behaved during the past several centuries, and thereby place the recent drought (or projected climatic change) within a long-term context.

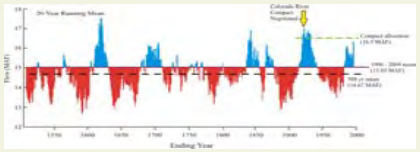
A new set of updated streamflow records for the Upper Colorado Basin was produced that spans the last 500 years (Woodhouse *et al.*, *Water Resources Research,* 2006). These long-term records illustrate that the Colorado River is highly sensitive to variations or shifts in climate, and that severe, sustained droughts are a defining feature of the Upper basin.

**Findings**

•Average annual flow at Lees Ferry is approximately 14.7 million-acre-feet (MAF), substantially lower than either the 20th century mean (15.2 MAF) or the 1922 Compact allocation (16.5 MAF).

•When extremely low flows occur at Lees Ferry, low flows usually also occur in major tributaries upstream.

•The recent drought in the Upper Colorado is extremely severe – tree rings record only one five-year period (1844 – 1848) that was as dry.



*Reconstructed flow of the Colorado River at Lees Ferry. Blue and red shading indicates periods when flows were above or below the 1906 – 2004 average, respectively. Adapted from Woodhouse et al. (2006).*

•Despite the severity of the recent drought, there is evidence of longer duration droughts in the past. The Lees Ferry reconstruction contains one sequence each of six, eight, and eleven consecutive years where flows were less than the 1906-2004 average.

Future work will extend streamflow records for gauges in the Bureau of Reclamation's Colorado River System Simulation model, beginning with the Little Colorado River near Cameron AZ (Meko, in preparation).

## Economics: Cost Effective Strategies for Supply Reliability

The **economics component** of the project investigates temporary dry year water transfers as a tool to cost effectively improve supply reliability.

There are four primary project objectives:

- Identify and evaluate the effectiveness of dry year strategies currently being employed in the western US and worldwide to improve dry year supply reliability.
- Evaluate how enhanced predictive capacity can be incorporated into the identification and structure of dry year supply reliability strategies.
- Develop a method for estimating on farm values for irrigation water to inform irrigation negotiations.
- Analyze net returns over variable costs (NROVC) for western Arizona crop productions to provide a useful baseline for dry-year forbearance negotiations.

It is possible to structure supply reliability strategies to:
- Address dry year needs
- Establish price
- Negotiate terms of transfer
- Preserve local agriculture base

**Findings**

- Payments in voluntary programs need to be equal to or greater than NROVC to be attractive to irrigators
- NROVC are much higher for vegetables than for field crops in Yuma and La Paz counties.
- Requests for participating growers to forbear irrigation should come in early winter before they have begun field crop production.
- If shortages can be predicted, then forbearance options can be exercised for field crops and the conserved water can be banked for the following summer.
- Pre-planning for cost-effective forbearance requires:
  1) Capacity to predict water supply shortfalls in Dec-Feb accurately enough to inform negotiations for the following summer.
  2) Adequate storage capacity available at a reasonable cost to carry unused irrigation water into future seasons and years.

**Figure 4.** *Irrigated agriculture in Arizona represents an opportunity for voluntary, temporary transfers from agricultural to municipal and environmental uses.*

## Management: How can improved predictive capacity support long range planning efforts?

The **water management component** of the project focuses on the challenges and priorities articulated during the stakeholder interaction phase of the project.

Meetings with water managers and stakeholders revealed three specific research priorities, and this stakeholder interaction directly framed the research inquiry to include:

- Bracketing and communicating uncertainty.
- Understanding basic assumptions of RiverWare (the suite of Colorado River operations and planning models).
- Integrating changing climate information into statewide management plans and projections.

**Findings**

This project distills the key sources of uncertainty embedded in river operations and planning models. This analysis identifies that:

• Starting reservoir levels act as a chief source of uncertainty over a three- to five-year simulation outlook.

• Climatic variability, depletion projections (Fig 5) and variations in operating rules become increasingly important sources of uncertainty in modeled reservoir storage levels in the Basin.

Participants in Arizona's intrastate Colorado River Shortage Sharing Stakeholder Workgroup articulated a set of recommendations for integrating scientific, policy, and technical uncertainty into long-term planning decisions. These recommendations emphasize that model simulations must include transparent and well articulated assumptions; identify drivers of uncertainty in simulations, and evaluate best- and worst-case scenarios.

The water management team publishes a quarterly e-newsletter to provide updates on water supply reliability issues in the Colorado River Basin, including drought conditions and water shortage planning. This newsletter also provides answers to many general questions raised by stakeholders through articles that span all four disciplines of the project.

*To receive the e-newsletter, email dgarrick@email.arizona.edu*

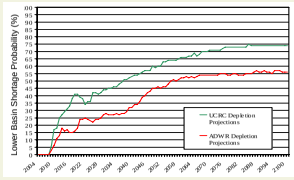



***Figure 5.*** *With demand still increasing in the Upper Colorado River Basin (UB), projected UB depletion is a focal assumption in model runs conducted for long range planning purposes, such as the development of shortage guidelines. The chart above depicts the divergence in lower basin shortage probability according to the underlying depletion projection. The Arizona Department of Water Resources (ADWR) and the Upper Colorado River Commission (UCRC) offer two commonly modeled depletion rates for the Upper Basin.*

*Data Source: ADWR Colorado River Shortage Sharing Stakeholder Workgroup, 2005*

# VOLUNTARY IRRIGATION FORBEARANCE TO MITIGATE DROUGHT IMPACTS: ECONOMIC CONSIDERATIONS[1]

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Katie Pittenger, Graduate Research Assistant
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***October 6, 2006***
***Comments to: bcolby@email.arizona.edu***

## INTRODUCTION

The balance between limited and variable water supplies and growing demands in the Colorado River Basin means that costs of drought-induced supply variability have the potential to be widespread and acute, affecting many different sectors of the economy. Regional water management strategies to enhance dry-year supply reliability are essential to minimizing susceptibility to drought-induced shortage. This report examines voluntary, temporary dry-year irrigation forbearance as a mechanism to mitigate drought impacts for water users susceptible to dry-year water supply shortfalls. Many other fields of expertise are essential to designing a well accepted and cost effective forbearance program. This report focuses on economic considerations as a complement to work being conducted in other disciplines.

This report provides analyses of on-farm irrigation water values in La Paz and Yuma Counties in western Arizona based on crop-specific net returns over variable costs (NROVC). NROVC indicates the ***minimum*** payment offer an irrigator would need in order to consider refraining from irrigating a specific crop. This can be a useful benchmark in negotiations over dry-year forbearance agreements. This calculation is straightforward, transparent and easily modified to reflect changes in input and output prices and federal farm program payments. The basic methodology established in this report can be applied to other locations and crops beyond those investigated for this research.

### The Lower Colorado River Basin In Context

In Arizona, the construction of the Central Arizona Project (CAP) fundamentally changed the nature of Arizona's water supply. The CAP delivers approximately 1.5 million acre-feet of Colorado River water to municipal, agricultural, and Native American interests in central Arizona. The CAP was constructed to

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[1] This report represents one facet of a multi-pronged project (Enhancing Water Supply Reliability Through Improved Predictive Capacity And Response) which examines ways to enhance Arizona's water supply reliability from the Colorado River. The Principal Investigators on this project include, in addition to Colby, Kathy Jacobs, Arizona Water Institute; David Meko, Laboratory Of Tree Ring Research and Bart Nijssen, formerly with the Departments of Hydrology and Water Resources and Civil Engineering. at The University Of Arizona.
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provide an additional source of surface water to offset groundwater overdraft in central Arizona. California's eventual support of the CAP was contingent on Arizona accepting a junior CAP priority status, meaning CAP water users would be among the first to experience reduced deliveries in the event of shortage on the Colorado River system. Uncertainty surrounding Upper Basin development, shortage sharing criteria, and tribal reserved rights has created concern over the CAP's junior priority.

The Arizona Water Banking Authority (AWBA) was established in 1996 with several objectives: to protect Arizona against Colorado River shortage or CAP supply disruptions by storing any unused apportionment in underground aquifers within the state; to support the management objectives of the Arizona Groundwater Code; to promote the settlement of Native American water rights claims; and to support California and Nevada in meeting their supply requirements while protecting Arizona's allocation through facilitating interstate water banking with water stored in Arizona (Arizona Water Banking Authority).

Temporary water transfers are not new to Arizona but have generally involved transfers of surplus CAP water and transfers of agricultural water to meet municipal needs. Since 1987, almost 4.5 million acre-feet of water have been temporarily reallocated in the State via lease transactions. Approximately 87% of these temporary transactions involved CAP water (Pittenger, 2006).

Nevada's 300,000 AF/year allocation of Colorado River water, which once seemed plentiful to support southern Nevada's needs, is no longer perceived as adequate given southern Nevada's urban population explosion. Unlike the other Lower Basin states, southern Nevada has a small amount of irrigated acreage (Virgin and Muddy River Basins), which limits the potential for transferring water out of local irrigated agriculture to municipal use. Nevada has explored a number of options to increase its access to Colorado River water. In late 2004, Southern Nevada Water Authority (SNWA) reached an agreement with Arizona to allow Nevada to store unused Colorado River water in Arizona's underground aquifers (Southern Nevada Water Authority, 2006). Under the agreement, which is an amendment to a 2001 groundwater banking agreement, Nevada paid $100 million to Arizona in 2005 and starting in 2009 will make 10 annual payments of $23 million. In exchange, Arizona will store up to 1.25 million acre-feet of Colorado River water for Nevada's future use.

The Lower Colorado River Basin periodically experiences consecutive years of serious drought, characterized by low rainfall and snowpack, reduced runoff and streamflows, and drawdown of storage reservoirs. For instance, between 2000 and 2004, inflows into Lake Powell were well below average, and by April, 2005 Lake Powell had reached a low elevation of 3,555 feet or 33% of live storage capacity (Bureau of Reclamation, April 2006). Although 2005 was wetter than the previous years, inflows into Lake Powell are expected to be below average again in water year 2006 with storage in Lake Powell likely to decline.[2]

[2] This research project also considers tree-ring reconstructions which give a much longer perspective and affirm the potential for a drought in the Colorado River Basin more extreme and sustained than any in recorded history (Meko, 1995; Woodhouse et al 2006).

Managing water supplies to minimize potential damages of climate-related supply shortages is a critical challenge facing Arizona. Temporary and voluntary dry-year water transfers represent one viable mechanism to reallocate water during drought and to avert dry-year shortages in vulnerable locations and water use sectors.

## Economic Rationale for Dry-Year Transfers

Temporary water transfers to mitigate drought impacts will typically involve irrigation water because agriculture accounts for such a substantial proportion of water use in the Southwest. Low financial returns to irrigating various field crops, and the relative seniority of some agricultural water allocations, make transfers out of agriculture attractive to those urban and industrial users which would face high costs if their supplies were curtailed. In addition, public programs to protect and restore water-dependent habitat may be potential lessees of irrigation water during dry periods.

Many water rights in the western states are governed by prior appropriation, a "first-in-time, first-in-right" system. Irrigators across the West hold senior water rights while municipalities and newer uses such as environmental flows or recreation have a junior priority. In the event of shortage, irrigators with senior water rights will receive their full allocation, while junior right holders may be shorted. Lower priority water users face high economic and political costs during water shortages. However, these losses can be mitigated through voluntary negotiated transfers. Such transfers can be financially feasible when the marginal value of the water used to irrigate low-value crops is markedly lower than the marginal value of additional supplies to the user who faces losses when supplies are short. When different types of users have differential marginal values for water during drought, then the water can be voluntarily re-allocated to ameliorate high cost drought impacts while still paying farmers more than they would have earned irrigating crops. However, other costs of implementing the transfer must not be so high as to make the dry-year lease unattractive to those seeking to augment their dry-year supplies. To summarize, a necessary condition for voluntary irrigation forbearance arrangements is: those parties wishing to enhance their own dry-year supply reliability must be willing and able to pay an amount that, at minimum, exceeds irrigators' foregone NROVC plus program administrative and implementation costs. This implies that forbearance programs are more affordable to the extent that they target irrigation forbearance for low profitability crops and that program implementation costs are kept low.

The temporary nature of such transfers has several advantages. While effective in mitigating the costs of drought-induced supply variability, dry-year transfers are not suitable to provide long term supplies for population growth (as a temporary "borrowing" of water from an established user). This means they cannot be dedicated to support growth once drought has ended, which would make them unavailable as a buffer in future dry periods. Further, they are less costly in both financial and political terms than permanent acquisitions of agricultural land and water, and they generally engender less heated opposition over potential third party impacts.

## Shortage Sharing in the Lower Colorado River Basin

Each year, the Secretary of the Interior evaluates the water supply situation on the Colorado River for the Lower Basin States and declares the year to be surplus, normal, or shortage. While regulations and operating criteria have been defined for normal and surplus conditions, the implications of a shortage declaration have never been explicitly defined (Bureau of Reclamation, March 2006a). Increasing pressure on supply, drought, and the corresponding drawdown of the Colorado River system's two main storage reservoirs (Lake Powell and Lake Mead) have prompted the development of guidelines on how shortage conditions would be declared, managed, and shared among the Basin States.

In 2005, a formal process began to develop shortage sharing guidelines for the Lower Basin and coordinated management strategies for Lakes Powell and Mead under low reservoir conditions (Bureau of Reclamation, March 2006b). Given the potential for environmental impacts of the shortage sharing and coordinated management guidelines, the Department of the Interior began a formal National Environmental Policy Act (NEPA) process. This will include the preparation of an Environmental Impact Statement (EIS) to evaluate probable environmental consequences for a range of alternative operating scenarios.

A Scoping Report, released by the Bureau at the end of March, 2006, represents the culmination of a 5-month scoping process aimed at soliciting public input into the necessary extent of operations alternatives. Four principles are identified in the report as fundamental requirements for alternative operating scenario proposals (Bureau of Reclamation, March 2006b). They are:

(1) Develop criteria for declaration of a "shortage" that would initiate shortage sharing among the Lower Basin States below their annual 7.5 million acre-feet allocation of Colorado River water;

(2) Develop coordinated management guidelines for Lakes Mead and Powell, particularly under low reservoir conditions;

(3) Develop guidelines for increasing the flexibility of storage and delivery of water in Lake Mead (including non-system, exchanged, and conserved water) to enhance the ability to meet the needs of water users, particularly under low reservoir conditions; and

(4) Incorporate the elements of the new guidelines (1-3 above) into the existing Interim Surplus Guidelines.

New shortage guidelines will also be interim, persisting until 2025, so that modifications can be made based on experience gained and lessons learned during the interim period. The Bureau expects to submit a draft EIS by the end of 2006, a final EIS in November, 2007, and a Record of Decision by the end of that year.

One component of the Seven Basin States' preliminary proposal for Colorado River interim operation guidelines includes the initiation of an "Intentionally Created Surplus" program (Bureau of Reclamation, Feb 2006). The Intentionally Created Surplus (ICS) program provides a framework for Colorado River water users in the Lower Basin to generate ICS credits to be stored in Lake Mead by

engaging in extraordinary conservation, thereby helping to avoid shortage in the Lower Basin and maintaining the elevation of both Lake Powell and Lake Mead at levels higher than would otherwise have been possible.

The chief methods of extraordinary conservation are irrigation forbearance agreements, canal lining, and desalination programs. Lower Basin states would be permitted to create ICS credits through extraordinary conservation only up to specified volumes. California can conserve up to 400,000 AF/year, Nevada is allowed 125,000 AF/year, and Arizona's maximum ICS credits are 100,000 AF/year. Each year when annual water orders are placed for the following year, states with ICS credits can request the recovery of those credits in addition to their water order for the year. ISC credits are also available, upon approval by the Bureau of Reclamation, in the case of extreme weather or water emergency situations (Bureau of Reclamation Feb 2006). Storage of ICS water in Lake Mead is related to adoption of proposed coordinated operations for Lakes Mead and Powell.

A demonstration ICS program is underway in 2006, under an agreement between the Metropolitan Water District of Southern California and the Bureau. The program is designed to create 50,000 acre-feet of ICS water through extraordinary conservation occurring under the Palo Verde Irrigation District (PVID) Land Management, Crop Rotation and Water Supply Program initiated by MWD and PVID in 2004. (For full details on the demonstration program see http://www.usbr.gov/lc/region/programs/AgreementwithMWD.pdf).

## ECONOMIC CONSIDERATIONS IN DESIGNING DROUGHT RESPONSE POLICIES

The economic impacts of drought are diverse and can reach far beyond an area actually experiencing a drought. The U.S. incurs an estimated $6-$8 billion in drought-related costs and losses annually from economics sectors such as agriculture, energy, recreation, municipal and industrial, governmental, and the environment (NOAA, 2002).

The effects of drought in agriculture, the largest water user in the western U.S., can be acute. Agricultural costs associated with drought include crop failure, reduced crop productivity, increased susceptibility to disease and insects, and wind erosion. In response to such costs, there are a variety of federal programs to mitigate drought impacts on farmers. Droughts' effects on agriculture also affect related industries such as farm input suppliers, food processing, farm labor and financial institutions.

Drought can force municipalities and industrial users, who often hold junior water rights, to incur high costs of acquiring supplemental supplies or to incur losses due to the inability to use their customary quantities of water. Further, hot dry conditions stimulate greater residential and commercial demand for outdoor water use to maintain landscape investments and turf.

Drought can also have severe implications for energy production. The ability to produce hydropower is impaired when streamflow and reservoir storage levels decrease. Moreover, higher temperatures typically associated with drought simultaneously bring with them increased energy demand.

Balancing environmental needs with power production, which is always a challenge, becomes even more difficult during drought.

Drought also affects recreation and tourism industries. Opportunities for skiing, boating, rafting, fishing, hunting and bird watching can be diminished because of drought. And this affects those sectors of the economy that rely on business generated by recreation/tourist activity.

The economic implications of water supply variability in the western U.S. are harsher today than they were years ago. Traditional supply-side approaches to water resource development, such as reservoir construction, have become less economically and environmentally viable. Yet rapid population growth and environmental considerations place additional demand on the West's water supplies, resulting in more intense competition for water and higher costs across many water using sectors during drought-induced shortages. These circumstances have prompted efforts to explore other methods for minimizing vulnerability to supply variability, such as water transfers via voluntary negotiations.

## Voluntary Drought-Responsive Water Transfers: Background

The following section provides a more in-depth look at various forms of water transfers which have been identified in the literature as promising means of addressing drought-induced supply variability. Colorado and California are home to some of the most established "water markets" in the world (Landry and Anderson, 1999). In Colorado, urban areas have a reliable supply of water partly because of the growing, active water market. California has supported ag-to-urban transfers through the establishment of emergency drought water banks, federal water acquisitions for environmental purposes, and a growing number of arrangements for short term water transfers.

Weinberg (2002) examines economic aspects of voluntary ag-to-urban transfers in central California. The Central Valley Project (CVP) in California provides irrigation water for over 2.5 million acres of cropland, producing crops worth over $3 billion annually. Weinberg develops an optimization model using agricultural and urban benefit functions to analyze the economic impact of various policy instruments, including voluntary water transfers. The dataset is a mixed panel with a time series of crop and water use for multiple water districts using CVP water. Other variables include total output, crop prices, and county-level soil and climate variables such as number of frost days, average precipitation, and average slope percentage. Urban water demand functions are based on published measures of demand elasticities in California. Voluntary water transfers are found to be a cost effective means to acquire water for urban needs, with results suggesting that CVP farmers would sell 342,000 acre-feet to urban users at $32/af. This would decrease crop revenues by $10 million and create $36 million in urban gross benefits, $11 million of which would be transferred to irrigators for water payments. Thus, farmers' total revenue would increase by $1 million and urban net benefits would increase by $25 million. The model results are consistent with observed ag-to-urban transactions in California.

The agricultural sector in Spain has been engaged in water transactions since the 15$^{th}$ century (Maass and Anderson 1978), and voluntary water transfers have occurred for years within the agricultural sector in

the western U.S., typically among farmers within the same irrigation company or district. Economic and environmental conditions today are encouraging transfers between sectors, such as agriculture to urban. Such transfers provide an opportunity to make water supply systems more drought resilient (Lund *et al.*, 1992).

Examples of developing western water markets include: an electronic trading board in the Westland Irrigation District in California where farmers buy and sell water; active water transactions in Utah and Nevada in response to rapid urban growth; and an irrigation forbearance program in Oregon aimed at enhancing streamflows to protect endangered fish. Water transactions also occur outside of the U.S. in countries such as Mexico, Australia, South Africa and Chile. In Chile, for example, dry-year options have been employed to avoid the costs of buying water rights that are only needed during dry years.

In every political jurisdiction, transfers are subject to public agency oversight with the intent of protecting other rights holders and public interests. The approval process, however, can be lengthy and costly and may discourage desirable transfers. States such as Oregon and Colorado have recognized that bureaucratic delays create costs and uncertainties, and have tried to mitigate the problem by assuring more rapid decisions on temporary water transfer applications (Landry and Anderson, 1999).

Water transfers can be permanent or temporary. When water right ownership actually changes, the transaction is considered as a permanent transfer and provides a long term supply augmentation. Historically, the majority of permanent transfers have occurred between agricultural users and urban buyers. When potential buyers are more concerned with enhancing supply reliability during drought or other shortage situations (e.g. flooding, contamination), temporary transfers may be more appropriate.

Temporary water transfers occur in many different forms. In “spot market” transfers, the price is often established by a bidding process. With water banks, lessors provide water to the water bank for a fixed price and lessees obtain water from the bank at a higher fixed price, set to cover the bank’s administrative and technical costs. During drought, water banks can reduce urban suppliers’ need to pursue more expensive and disruptive permanent acquisitions.

Contingent transfer agreements, or dry-year options, are another form of reallocation that may be useful to enhance dry-year supply reliability. These temporary transfers, which are implemented contingent on supply shortage, are contractual agreements that extend over a specific time period which can range from a few months to many decades. Contingent dry-year transfer contracts between senior and junior water rights can maintain supply reliability for juniors.

## Challenges in Forbearance Program Design

The design of forbearance programs must account for legal procedures and policies for transferring water, which vary from state to state and within states. In instances where a transfer involves changes in place or purpose of use specified in a water right, state administrative requirements must be satisfied. While some states have enacted legislation to facilitate temporary transfers during drought or other emergency

supply situations, both short term and long term transfers can encounter significant legal and economic challenges.

Quantifying the amount of "wet" water that can actually be transferred to a new place and/or purpose of use can be a difficult task. The portion of a particular farm's customary water applications that is no longer consumptively used when land is fallowed or crop patterns are altered is often difficult to determine. Seepage, evaporation, and natural accretion also create uncertainty that surrounds the estimate of how much wet water is actually available for transfer. If this issue is not addressed by developing standards to estimate consumptive use, the amount of "paper water" transferred could exceed actual consumptive use. Allowing this larger quantity to be transferred can be detrimental to downstream surface water users, nearby groundwater pumpers and water-dependent habitat. Screening out "paper water" (that is, legal access to water that has not been exercised and, therefore, whose forbearance will not provide "conserved" water) is an important and controversial task in any forbearance program. Water acquired to improve dry-year reliability needs to be water that is physically available for use during dry periods and for which reduced consumptive use by the forbearing party can be verified.

As an example, in Nevada's Truckee-Carson Basin water was needed for dry-year endangered fish recovery programs and to buffer drought impacts on urban areas. Some agricultural water rights had not been consumptively used for years, meaning that water became "paper" water, not "wet" water. It became the task of the organization that arranged transfers for environmental needs to coordinate with the Nevada State Engineer's office to identify which agricultural water entitlements had regularly been consumptively used. This was necessary so that water acquisitions from irrigators actually would firm up dry-year supplies and improve fish flows. The process was politically charged, protracted and contested by irrigators.

In addition to issues over quantifying the amount to be transferred, conveyance, storage, and treatment of the transferred water can be significant considerations. In regions with extensive conveyance and storage systems, there is a higher likelihood of successful dry-year water leases. The price per acre-foot transferred influences the quantity demanded and supplied. Thus, the cost of dry-year water, whether set by negotiations, by a water bank, or by a public agency has important implications for the number and character of transfers. Conveyance, storage, and treatment costs need to be weighed, along with costs such as legal fees, public review processes, technical studies, and third-party compensation (Lund and Israel, 1995).

Forbearance programs are more readily negotiated and implemented when a sound working relationship exists between agricultural water districts and their member irrigators. Negotiating the division of proceeds from dry-year leases between the district and the growers (who forgo income from crop production) can be challenging. Irrigation districts often undertake management and oversight obligations associated with implementing forbearance agreements and the district may hold the water entitlement that is delivered to its member growers. Forbearance contracts often are negotiated between the parties seeking more reliable supplies and an irrigation district, with the district negotiating payment for forbearance with individual member irrigators. In the 1980s in Utah, for example, an electric power generating facility needed

45,000 acre-feet of water to operate its plant. The power facility was located in a rural, agricultural region of Utah, and the local communities were concerned about the effects of the plant on water supplies in their area. When the power company began seeking water rights, the communities involved set up an arrangement in which all members of the irrigation companies were invited to participate in making water available. The power company negotiated with the local irrigation districts and ultimately purchased a package of 45,000 acre-feet of water that was composed of water rights of relatively small quantities from many different irrigators (Saliba and Bush, 1987).

Major impediments to the development of successful forbearance programs are unfamiliarity with the process (by agencies, irrigators and water districts), lack of program momentum, and disagreements among growers and districts over distribution of forbearance payments. One approach to addressing lack of momentum is to offer an early response bonus to farmers who participate in the program in its opening stages. To partially address divisiveness over forbearance payments, each irrigator in a specific district can be given an option to lease 10% of their water in a given year so that negotiations and trades in these options can occur between farmers. That is, if one farmer wanted to lease out more than 10% of his water, he could buy an option from a farmer who did not wish to lease out any water. This means that even those farmers who did not choose to lease water would be involved in, become familiar with, and benefit from the program. This avoids a "divide and conquer" approach, which characterized some early water transactions between cities and agriculture. Each district member receives some form of benefit, and the revenues from the acquisition program are spread more broadly.

The overall costs of dry-year options must be evaluated and weighed against the additional reliability the options will provide to municipal supply and fish recovery programs. Dry-year options are more expensive on a per unit basis (per each acre-foot made available) than outright water purchases. The desire to avoid the third party impacts associated with permanent fallowing and to maintain a vigorous agricultural sector is the chief impetus for considering drought-triggered transactions.

## Third Party Impacts

Third party impacts can generate significant controversy and opposition to water transfers, preventing some transfers altogether and making others more costly. Agriculturally-linked rural communities and local governments (such as irrigation districts and counties) often respond to proposed water transfers out of agriculture with suspicion and alarm, concerned that movement of water away from local agricultural uses will undermine the local economy by reducing business activity and property values.

Due to the wide variation in the local economic consequences of water transfers out of agriculture, each case must be examined on its own merits. A number of economic studies have examined actual transfers and have modeled the effects of proposed transactions. Studies of transfers out of agriculture find that local economic impacts are proportionally smaller than the amount of irrigated land that is fallowed, even when the water is moved to a new use away from the area-of-origin (Howe *et al.*, 1990; Checchio, 1988). For instance, fallowing 10% of the irrigated land in a county will NOT cause a 10% reduction in net

farm income from irrigated crop production. The consistent findings of economic impacts being proportionally smaller than the percent of irrigated acreage fallowed are due to several factors: a) farmers choose to fallow their lowest value crops and their least productive acreage, b) a portion of water payments received by farmers is generally spent in the county from which the water is exported, and c) income from crop sales is a small portion of county income in nearly every rural county in the West. In the entire Colorado River Basin, less than a handful of counties are classified by the USDA as ag-dependent (counties are classified as agriculturally dependent when 15% or more of county income comes from farming, USDA, 2004). Rural county households rely on income coming from off-farm employment and government payments more than on income from crop sales. Water transfers can stimulate off-farm jobs and income.

Even though water transfer impacts are small in the context of a region's economy, they may be significantly concentrated in certain businesses or specific agricultural communities (Howe *et al.*, 1990). The parties most affected by proposed transfers generally are not those who have water to sell, but rather are suppliers of inputs and labor (farm workers) to growers and post-harvest processing enterprises (such as cotton gins).

Several approaches can be used to address local impacts. Transactions can be designed in ways to help minimize negative third party effects and maintain agricultural activity in rural areas. Making transfers contingent on drought conditions is one approach to preserving an agricultural base, as farming will occur as usual in normal years and growers can be adequately compensated in dry years to allow them to remain in business. Changes in crop mix could be considered as a means to address impacts as well. A University of California Davis study found that alfalfa is water intensive but employs relatively little labor compared to fruit and vegetable crops, so that alfalfa fallowing would have different impacts on ag-linked jobs than fallowing more labor-intensive crops (Martin, 2003; Howitt, 2002). Other approaches include paying for on-farm water conservation practices and transferring only the water conserved, and rotating acreage fallowed (and water lease payments) among landowners to maintain the baseline agricultural economy. Lease payments can include incentives, such as bonus payments, to growers to reinvest their lease payments in local agriculture and to spend payments at local businesses.

A "rebuttable presumption" approach can be adopted in which standard local economic impact models are used to estimate the magnitude of impacts. Regional economic models are a standard type of economic analysis. As with any set of models, analysts can choose assumptions that amplify or diminish economics effects. Nevertheless, reliable estimates of impacts can be made and evaluated. A multi-person expert panel, nominated by transfer proponents and opponents, can be used to evaluate impacts and make recommendations. Clearly documented impacts ought to be compensated in an affected local economy, not just to reduce conflict but also to avoid costs of economic dislocation and unemployment. Rural and urban areas in the southwest are bound together in an inextricable web of mutuality. Their economies are interdependent, as are farm and non-farm businesses. El Centro, Yuma, and Mexicali areas share some common landowners and common labor pools.

Compensation for impacts imposes a modest tax on the drought relief benefits of temporary fallowing. Most households in rural counties do not depend on ag-linked jobs. In non-metro Arizona only 17% of jobs are linked to agriculture, including provision of farming inputs all the way up the chain to retail sales of local agriculture products. Similarly in California, Colorado, and New Mexico only 18%, 20%, and 17% of jobs are linked to agriculture. Rural county per capita income grew 30% from 1999-2003 and percent poverty in farm households is the lowest in U.S. history.

People whose way of life changes involuntarily are understandably unhappy about it. Money does not change that, but it can address practical impacts on employment and agricultural linked business. Dry-year land fallowing programs are intended to avert serious economic dislocation among junior water users by paying farmers to forbear use of senior water. While rural communities may also benefit from these averted drought impacts, their opposition to water transfers may stem from fundamental and well-founded concerns that transfers signal a change in society's priorities and values for how water is used.

Well structured voluntary land fallowing agreements are an important regional drought response tool. To summarize, from the perspective of local economic impacts dry year leases have important advantages: a) drought-triggered fallowing cannot be diverted to support urban growth like permanent acquisitions do, b) land fallowing can be constrained and rotated so that only 10% is fallowed in any one year, c) incentives can be created for growers to reinvest fallowing payments in local area (such as bonuses for local spending of payments), d) standard methodologies can be adopted for estimating local impacts with a rebuttable presumption approach, and e) only modest land fallowing is needed for M&I dry-year purposes.

## Structuring Irrigation Forbearance Programs

### Water Banks

Water banks now are established in almost every western state, and although there are functional differences among the banks, each share a common goal of facilitating water transfers, taking on the role of broker, clearing-house, or market-maker while fulfilling other administrative and technical functions. In a report on western water banks by Clifford *et al.* (2004), a water bank is defined as, "an institutional mechanism that facilitates the legal transfer and market exchange of various types of surface, groundwater, and storage entitlements." Unlike a leasing program, which generally involves a single lessor who temporarily leases water from multiple sellers for a specific purpose, water banking involves interaction between multiple lessors and lessees to organize entitlement transfers.

The market structure is a critical component of a well-functioning water bank because it determines how participants interact and carry out transactions and also plays a role in price determination and the dissemination of market information. Buyers and sellers rely heavily on price and market information to locate trading partners and to evaluate price signals on the value of water, so adequate price and market information is essential to the development and functioning of a water bank.

The simplest type of bank function is as an information clearinghouse. Here, participants declare their intent to transact and most commonly, prices are determined through repeated, bilateral negotiations

between a single lessor and a single lessee. While the clearinghouse function does not necessarily eliminate price dispersion in thinly traded markets, it does reduce the transactions costs of identifying potential trading partners.

A fixed price structure, in which the price is fixed by the bank, is another framework employed by water banks. The bank, however, may not possess sufficient information to correctly estimate a market clearing price or to account for differences in quality and reliability of water rights within the region. Although the fixed price structure creates a sense of fairness and reduces concerns about price gouging and speculation, such a structure is unable to respond quickly to changes in market and climactic conditions. This limitation becomes acute during dry years because lack of a price incentive to bank water during wet years leads to insufficient banked supplies during drought.

A more flexible option is for buyers and sellers to negotiate prices themselves, along with quantity of water to be transferred as well as timing and location of delivery. This is the "clearinghouse" approach discussed previously.

Despite their potential for easing drought impacts, transaction activity in most banking programs tends to be limited. Water banks in the West are a relatively new concept in most regions and potential banking participants have limited experience. Also, the number and type of participants is typically restricted along with the types of allowable transfers (Clifford *et al.*, 2004). The Snake River water bank is an exception, having operated for several decades providing flexibility in Idaho's Snake River Basin.

**Dry-Year Options**

Agriculture represents over 80% of water consumption in the southwestern U.S., and much of what the hay and field crop acreage generate yields relatively low economic returns (Griffin, 2006). Because the cost of transferring water out of agriculture to other, higher-value uses is generally more feasible and cost effective than developing new water supplies, attention has increasingly been drawn to the potential for market transfers of agricultural water rights. Instead of ensuring drought protection by the purchase of senior water rights, which may generate significant third-party costs, "dry-year options" or "water supply option contracts" (Michelson and Young, 1993) can meet municipal water demands during drought.

A dry-year option is a contract or agreement between a farmer, group of farmers, or agricultural district and an urban water user to transfer water temporarily from agriculture to urban use during occasional critical drought periods. Such agreements can secure a source of drought water supply for cities and other users (Michelsen and Young, 1993). Dry-year options are exercised in pre-specified drought/shortage conditions. Agricultural water rights are maintained and agricultural water supply during normal supply conditions is not affected. This approach to addressing dry-year shortages is likely to be more cost effective and entails less third-party economic impacts than permanent acquisitions. When an option is exercised, irrigators temporarily cease irrigating cropland in exchange for an exercise payment. This payment must compensate them to a level *at least* equivalent to the level of foregone profit from crop production in order for the arrangement to be attractive to irrigators.

Option contracts can be one-time, short-term arrangements or can extend over decades. An example of the former would be an agreement negotiated during a winter when snow pack and reservoir storage are below normal, to be exercised later that same year if the region indeed finds itself in a shortage situation that threatens urban water supplies or fish recovery flows. Long term contracts can span many decades, giving those paying for forbearance the right to exercise an option to use irrigation water under pre-specified trigger conditions.

Dry-year options address two fundamental sources of uncertainty in water transactions: supply uncertainty and price uncertainty (Howitt, 1998). Options markets are a middle ground between pure spot markets and water markets for the permanent acquisition of water. Through options markets, risk can be spread between the suppliers and demander of dry-year supplies.

In spot markets, uncertainty is borne by demanders of water, as they must rely on thinly traded markets with uncertain supply to meet their inelastic needs. In the case of permanent transfer markets, suppliers must bear the uncertainty about the future value of their water and risk selling their water rights too cheaply. In both spot and permanent purchase markets, these uncertainties may be unacceptable for risk-averse potential transactors. Dry-year options contracts can spread the price and supply risk between suppliers and demanders of water during dry years. Demanders shift some of the spot market risk to suppliers by purchasing an option in advance of drought-induced supply shortage. Likewise, suppliers are relieved of some of the price risk inherent in permanent purchase markets, as options markets facilitate the *temporary* reallocation of water and the supplier would remain in possession of his water rights which may increase in value over time.

In addition to spreading these risks innate in water markets, options contracts can reduce third-party impacts of water transfers. The permanent transfer of water can have permanent economic consequences in the area of origin. Because options are seasonal and temporary in nature, the suppliers (typically farmers) continue normal farming operations in most years. In years the options are exercised, the growers likely will continue participating in the local economy and spend some of the options payments locally. In comparison to spot markets, options markets also allow rural communities more time to plan for changes in local spending patterns and job opportunities that occur as a result of temporary water transfers, thus minimizing the impact of those changes.

A key component of an option contract is the exercise cost. Defined as “the minimum amount that must be paid to a farmer to maintain the same level of net income in the event of option exercise,” the exercise cost is specific to individual farmers, depending on crop mix, precipitation, the quantity and cost of irrigation water, production costs, yields, and crop prices. Other costs that may factor into the exercise cost are short-run fixed production costs such as opportunity costs of family labor and management, taxes, depreciation, and cash overhead.

From the perspective of the party seeking more reliable dry-year supplies, the value of an option contract is a function of its cost (including approval and implementation costs) compared to both the cost of

the most likely dry-year supply alternative and the costs that would be imposed by a water shortage. By comparing option contract costs with alternative water supply costs and shortage costs, the present value net benefit of an option contract (PVNB) can be determined. A positive PVNB indicates an option contract is economically rationale; that is, the costs of the contract are less than that of other means of assuring dry-year supplies and are less than the costs that would be imposed by a supply shortfall.

The following provisions should be considered in structuring an option contract:

1. The exercise price, which is the payment to irrigators for the net value of forgone agricultural production each time the option is exercised, should be specified to change over time to account for differences in water values and market conditions. Changes can be tied to inflation measures, regional water or power costs or other indices acceptable to the parties. Such adjustment provisions make an agreement more stable over time and ensure that the parties share in the economic effects of changes in regional water values.
2. The quantity, location, infrastructure use (wheeling through a canal, for instance) and timing of water delivery need to be specified. The cost-sharing arrangements for using storage and delivery infrastructure should be specified, as well as the costs themselves.
3. Irrigators should retain the option of selling the water rights (or water project entitlements) that support the option contract before contract termination, but the option purchaser should likewise be guaranteed the chance to match a bona fide offer for water rights. This condition ensures supply security for the option holder, while maintaining the irrigator's ability to respond to attractive purchase offers over the life of the contract. Without such a provision, irrigators and irrigation districts may be reluctant to participate in an option contract.
4. Options contracts are most cost effective when they consider seasonal hydrologic and crop production patterns. For instance, in the fall a party seeking reliable supplies for the following year can pay an initial fee to secure an option to lease a specific quantity of water from an irrigator in the spring or summer months (Howitt and Hansen, 2005). Then, if the winter snowpack turns out to be poor and water supply shortfalls are expected, the option is exercised through growers ceasing irrigation of crops generating the lowest NROVC. Negotiating the contract ahead of need spreads the risks of drought-induced supply variability and reduces costs that may be associated with rapid negotiations to secure water in the spring.

Michelsen and Young conducted an empirical case study to evaluate the feasibility of exercising option contracts to provide water during drought from irrigated farmland in north central Colorado. The area is characterized by urban growth and pressures to purchase agricultural water by cities as well as a desire to maintain agricultural communities. The region generally had sufficient water in normal years to meet the demands of urban and agricultural users. In the early 1990s, Michelson and Young estimated the annual offering price for agricultural water to be $85/AF/year. Under varying river flow conditions and crop price conditions, estimated exercise costs range from $39 - $135/AF/year.

The PVNB equation is used to estimate the economic feasibility of water supply options for a base case scenario which is characterized by a 20-year contract term, a .05 annual exercise probability, an exercise cost of $90/AF, an initial water rights purchase cost of $600/AF, water rights management cost of $12/AF per year, real discount rate of 4% per year, and transactions and conveyance costs between the two alternatives assumed equal. The analysis concludes that Fort Collins can afford to pay a maximum option price of $295/AF and still benefit over the outright purchase of a water right. The option value is sensitive to water right prices and appreciation rates. The water supply option value increases as discount rates increase, because the opportunity cost of purchasing a water right increases while future option exercise costs and appreciation in water right prices are more heavily discounted. Conversely, as the appreciation rate of water right prices rises, the value of option contracts falls. Higher alternative water costs increase the option value significantly.

Long-term drought on the Colorado River has led to a growing recognition of the limits of the Colorado River storage system and the need to devise alternative strategies for coping with severe drought. Water supply option contracts represent a strategy for securing dry-year supply for urban areas while still maintaining an agricultural base. Many areas of the western U.S. already have the fundamental economic, infrastructure, and institutional framework in place to implement option contracts. Options contracts can be a viable approach to dry-year shortages under a wide range of economic conditions. In regions in which the transactions costs and conveyance costs are high, however, the net economic benefits of option contracts may be low or nonexistent.

## DRY-YEAR IRRIGATION FORBEARANCE IN PRACTICE

A review of past experience with dry-year temporary transfers provides practical guidance in structuring dry-year supply reliability strategies for the Lower Colorado River Basin.

There have been a number of dry-year transfer programs in California, as a result of drought in southern California, the Quantification Settlement Agreement, and low farm commodity prices (Howitt and Hanak, 2005). Metropolitan Water District of Southern California (MWD) has played a leading role in dry-year transfer arrangements to secure more reliable supplies in its extensive and highly urbanized service area. MWD secured the option to use water from Sacramento Valley irrigators with an upfront payment of $10/AF to the irrigation districts, and an additional $90/AF to growers who reduce their use of surface water for irrigation when the option is exercised. Participating irrigators have switched to less water-intensive crop production and use of groundwater in order to make surface water available to MWD. In 2003 almost 100,000 acre-feet of water were transferred via these options agreements involving the Sacramento Valley growers (Metropolitan Water District of Southern California, 2003).

An earlier example, also involving MWD, is a 1993 dry-year option arrangement whereby MWD secured option contracts from irrigators in the Palo Verde Irrigation District (PVID), located along the Colorado River in southern California. The agreement allowed MWD to call on water from participating PVID farmers generated by fallowing up to 25% of their land during dry years (Howitt, 1998). During a

two-year pilot program, PVID farmers fallowed 20,215 acres of land for $620 per acre. The land fallowing generated approximately 92,421 acre-feet of water at approximately $136/AF (Water Strategist, 1994).

The state of California also initiated a temporary transfer program in 1995, following several years of drought through the California Emergency Drought Bank. Options to use irrigation water were purchased in December of 1994 at $3.50/AF (Howitt, 1998). The exercise price, which would be paid by the option-holder in the event of a drought, was between $36.50 and $41.50 per acre-foot. 29,000AF of water were secured in this manner by end of 1994 for use before May of 1995. Improved hydrologic conditions, however, rendered the exercise of the options unnecessary.

Dry-year options to secure urban supplies have occurred in other areas. For example, an irrigator in Utah was paid $25,000 by a municipality to secure a 25-year option to use some of the irrigator's water. Then, each year the option is exercised, the municipality pays the irrigator a pre-set exercise fee, plus compensation for the value of the alfalfa the irrigator would have grown had the water not been transferred to urban use (National Research Council, 1992).

The Edwards Aquifer Region of Texas has also used dry-year irrigation forbearance to meet water demand in dry years. With the aim of raising aquifer levels, increasing spring flows, and ensuring drought relief for municipalities, the Pilot Irrigation Suspension Program (ISP) was initiated in 1997. The ISP, which paid irrigators to forego irrigation in the 1997 cropping season, was unique from other forbearance programs in the West in that it applied to groundwater instead of surface water, was implemented despite the lack of fully defined water rights, and was, in part, necessary due to federal court order to maintain spring flows to support endangered species (Keplinger and McCarl, 2000).

Eligible irrigators who submitted sealed bids to the Edwards Aquifer Authority (EAA) were selected based on four criteria: (1) location of the well and strength of the hydrologic connection to Comal Springs, (2) irrigation water requirements in 1995 and 1996, (3) irrigation equipment used, and (4) assurance of dryland crop on the proposed acres. The fourth criterion was included to minimize impacts to agriculture-dependant industries and to support community interests. Each bidder was assigned a score from 0 to 10 for each criterion, which was then summed. Per acre bids were divided by the sum to produce the final score, a lower score being more attractive.

Bids ranged from $116 to $750 per acre, with a median bid of approximately $300. In the end, the EEA accepted bids from 39 irrigators, totaling 10,067 acres of land. Payments to all enrolled irrigators, whose participating farm sizes ranged from 45.3 to 1,269 acres, totaled $2,295,132. To fund the program, the EEA received pledges totaling $2,350,000 from 32 water utilities and other larger pumpers.

An analysis of the 1997 ISP by Keplinger and McCarl presents a number of interesting findings. First, at an average price of $234 per acre, the ISP obtained forbearance on 10,067 irrigable acres in the Edwards Aquifer region. This payment is higher than what regional lease rates and land prices would suggest. This may be attributed to the newness of the ISP, its timing, collusion among farmers, and/or the belief that lower might affect future water prices or offers.

Keplinger and McCarl also analyzed the impact of the ISP on crop rotation and mixes of participating irrigators. Farmers who participated in the forbearance program tended to shift their crop mix from water-intensive corn, cotton, and vegetables to more water efficient sorghum and wheat. Despite a moderate reduction in farmer purchases of fertilizer, seed, and labor, secondary effects on the local economy appeared minimal. Farmers willingly participated in the pilot ISP and regional municipalities willingly funded the program. Although some modifications to the selection criteria, bidding process, and timing of the program could reduce program costs, the 1997 ISP proved to be a feasible and timely response to meeting needs during drought. The ISP was initially planned to be structured as a dry-year option, but such long term contracts could not be implemented in 1997 because a structure of tradable pumping permits was not in place yet.

Irrigators in the San Luis Valley of southern Colorado are implementing a voluntary irrigation forbearance program to preserve groundwater levels and prevent state regulatory actions to reduce aquifer overdraft (Oad and King, 2005). In Montana's Big Hole River Valley, irrigators have been paid to forbear from use of water entitlements in order to enhance flows for endangered fish, with some irrigators agreeing to forbear without compensation payments. The USDA Natural Resources Conservation Service offered ranchers from $40 to $60 per acre not to irrigate their hay meadows and pastures during a critical low flow period (Oad and King, 2005)

Chile is one of the few countries outside the U.S. that actively utilizes voluntary water transfers to manage water resources. Chilean farmers have negotiated options agreements amongst themselves to minimize dry-year supply variability for high value crops (Thobani, 1998). Instead of purchasing permanent water rights, farmers growing more profitable perennial crops secure the option to lease water for a season from a neighboring farmer engaged in annual crop production. Similar arrangements have been implemented in the U.S. Pacific Northwest between orchard and vineyard owners and nearby field crop producers.

## Proposals for Dry-Year Transfer in the Lower Colorado River Basin

Two recent proposals, one by a group of NGOs and one by the Yuma Desalting Plant/Cienega de Santa Clara Workgroup, both point to irrigation forbearance and dry-year options in Arizona and the Lower Colorado River Basin as a drought preparedness mechanism.

### Conservation Before Shortage

If a shortage were declared in the Lower Colorado River Basin, CAP water users would be among the first to experience reduced deliveries. At present, criteria have not been adopted to guide the Secretary of the Interior in declaring a shortage, though a scoping process to develop shortage guidelines is being undertaken by the Department of the Interior. Other concerned parties have also developed proposals for shortage sharing.

One such proposal is "Conservation Before Shortage" (CBS), a document developed by several NGOs, released in summer 2005 and updated in summer 2006 to reflect negotiations among the seven states and the ICS program (update referred to as CBS II, see

http://www.usbr.gov/lc/region/programs/strategies/alternatives/CBS2.pdf). CBS II discusses strategies to implement the ICS program and advocates consideration of extraordinary conservation program in Mexican agriculture. The CBS proposals advocate Colorado River drought management strategies aimed at avoiding extreme and uncompensated water shortages. The proposed conservation strategies hinge on the elevation of Lake Mead, such that when Lake Mead is drawn down to specific elevations, conservation through predictable, small-scale reductions in use by Lower Basin agricultural users is triggered. A fundamental element of the CBS strategy is voluntary forbearance agreements in the form of part-year forbearance programs, dry-year options, and other similar arrangements.

The CBS rational for voluntary forbearance is that conservation of between 200,000 and 600,000 acre-feet of Colorado River water could be generated through forbearance of just 4-11% of Colorado River water used for crop irrigation in the Lower Basin. Based on current prices of short-term water leases between farmers and irrigation districts or municipal water districts, as well as economic analyses of the net return of irrigation water, the 2005 CBS document suggests water conserved through forbearance arrangements could be acquired for $20 - $100 per acre-foot. An economic study undertaken by Environmental Defense suggests that over 2.3 million acre-feet of irrigation water is currently being applied to crops in Arizona and California that yield profits under $100 per acre-foot. Of this, about 1 million acre-feet are being applied to crops that generate profits under $20 per acre-foot (Conservation Before Shortage, 2005). The 2006 CBS proposal is one of the alternatives being evaluated in the Bureau's ongoing EIS process (Development of Lower Colorado River Basin Shortage Guidelines & Coordinated Management Strategies for Lakes Powell and Mead Under Low Reservoir Conditions, see http://www.usbr.gov/lc/region/programs/strategies.html).

**Yuma Desalting Plant Workgroup**

A consumptive use reduction and forbearance program based on voluntary, temporary irrigation forbearance has also been suggested as one of the solutions to controversy surrounding future operation of the Yuma Desalting Plant (YDP). As laid out in the April, 2005 document "Balancing Water Needs on the Lower Colorado: Recommendations of the Yuma Desalting Plant/Cienega de Santa Clara Workgroup," the operation of the YDP would have both positive and negative impacts in the Lower Basin and Mexico. Its operation would reduce the bypass of drainage water to Mexico from the Welton-Mohawk Irrigation and Drainage District (WMIDD) in southwestern Arizona. This would eliminate the need for additional releases from Lake Mead to make up for the bypass water, thus lessening the risk of shortage to Lower Basin water users. However, the operation of the plant would be costly, and the reduced bypass flow would likely have severe environmental consequences in the Cienega de Santa Clara, a large wetland in Mexico sustained by drainage water from WMIDD (Yuma Desalting Plant/Cienega de Santa Clara Workgroup, 2005).

One component of the workgroup's recommendations is a Basin-wide pilot consumptive use reduction and forbearance program. The idea behind the program is to pay farmers to voluntarily reduce their use of Colorado River water for irrigation and then credit the unused water to offset the obligation of

the bypass flow. The irrigation forbearance could occur in the long term, on an annual basis, or intermittently through mechanisms such as dry-year options.

Participation in the forbearance program would be open to eligible irrigators in the U.S. and in Mexico. The workgroup suggests that a target volume of water conserved through forbearance be tied to the elevation of Lake Mead, available funding, or another related limit. The pilot program would be undertaken for a defined period of time, at the end of which it would be determined, based on cost and effectiveness, if forbearance should be phased in as a component of the long-term YDP plan.

## ECONOMIC VALUES FOR AGRICULTURAL WATER

Information comparing the economic value of water across different uses is an important water management tool. In a water-short West, competing demands among various water uses create economic pressure to transfer water across uses during drought. Data on the economic value of water in different uses help parties negotiate fair prices for water transactions. A variety of methods have been developed.

Because agricultural water represents such a substantial portion of consumptive use in the West and because drought impacts in other sectors can be reduced by voluntary water out of low-value agriculture to higher value uses during times of shortage, most water transactions will necessarily involve agricultural water. As such, accurately valuing irrigation water is an important component of structuring and negotiating dry-year transfers. Young (2005) describes several widely-employed methods.

### Water-Crop Production Functions

In this approach, on-farm economic value of irrigation water is based on a water-crop production function. A water-crop production function models the link between the application of water and crop yield. In other words, it defines a relationship between a specific level of input application (water) and its effect on output (crop production). These functions are crop, location, and soil specific and depend on assumptions about the level of other crop production inputs such as fertilizers, pest control, etc. Crop-production functions are typically estimated based on expert opinion but can also be approximated using field experiments and computer simulation. The application of this approach is limited to locations and crops for which accurate up-to-date water crop functions are available.

### Market Price Comparison

Another method for valuing irrigation water is the direct observation of transactions prices in voluntary water transfers. Such observations provide insight into users' valuation of short-term leases of irrigation water or the permanent purchase of agricultural water rights. In theory, transactions negotiated in a well-functioning market will reflect the economic value of water, which would fluctuate with its level of scarcity. In dry years, for example, the equilibrium value of water would be higher than in comparably wetter years because in the short run, water demands are price-inelastic. This makes assessing the long-term value of water using short-term lease rates potentially problematic. Other complications associated with this method include inadequate transaction data and constrained water markets (Young, 2005). Application of

this approach is limited to regions with regular, voluntary transactions and access to price data, which is sometimes kept confidential by the parties to the transaction.

### Residual (or Farm Budget) Approach

The most common method for valuing irrigation water is the residual or farm budget method, which involves crop production cost and return analysis. Statistically estimating the marginal physical productivity of irrigation water using a crop-production function based on field data would be a more accurate method, but crop production functions in most regions and for most crops have not been developed (Gibbons, 1986). Thus, crop-budget analysis is employed as an alternative method to infer the return to water for production of a specific crop in a specific location.

The first step is typically to generalize to one or more representative farm models the approximate soil type, climate, labor supply and other crop production inputs, and cropping patterns for farmers in a specific area. A table detailing operations and inputs for each crop is constructed based on the representative farm. Data on the steps in the production process, timing, required production resources, and resulting outputs are generally obtained from farmer and extension agent interview to produce a crop- and location-specific crop budget. This data is then used to calculate and display net returns over variable costs per acre for each crop. This value represents the on-farm economic value of water in crop production and is calculated by subtracting variable production costs (exclusive of water costs) from gross returns per acre.

Although this approach can be fairly straightforward from an accounting perspective, biases that arise in the data gathering process can be nontrivial. Young (2005) warns that farm budget analyses are sensitive to the assumptions made about the nature of the production function, as well as input and output prices and quantities.

### Arizona Agriculture: Background

Arizona's semi-arid to arid climate necessitates the application of irrigation water on almost all agricultural acreage in the state, and agriculture represents the largest consumptive use of water in Arizona (Tadayon, 2005). However, rapid population growth over the last decade has placed increasing pressure on the state's water resources. From 1990 to 2004, the population of Arizona increased approximately 56.4%, swelling from 3.67 million in 1990 to about 5.74 million in 2004 (U.S. Census Bureau). Correspondingly, water withdrawal for municipal use has steadily increased and now represents the second largest consumptive use sector in the State (Tadayon, 2005).

Irrigation water in Arizona comes from three primary sources: (1) Colorado River surface water directly from the mainstem or pumped through the Central Arizona Project canal; (2) surface water from other major Arizona streams; and (3) groundwater (Governor's Drought Task Force Irrigated Agriculture Work Group, 2004). This section examines potential on farm costs of voluntary, temporary transfers of mainstem Colorado River surface during drought to support municipal and environmental water needs.

Over 60% of the West's total sales of irrigated crops come from high-value orchards, berries, vegetables, and nursery crops, though these high-value crops occupy only 15% of harvested irrigated land.

By contrast, field and forage crops, which accounted for the remaining 40% of total value of sales, occupy 71% of irrigated acreage (Gollehon and Quimby, 2000). This variation in acres irrigated and the contribution of various crops to farm revenues means irrigators have flexibility in adjusting to changes in water supply. Water shortages can be addressed by shifting cropping choices to maintain production of higher-valued crops. Water leases represent an opportunity for farmers and water suppliers to transfer water and maintain higher-valued crops during drought.

Irrigated agriculture is an important contributor to Arizona's economy; it is estimated to contribute $6 to $7 billion dollars annually to the overall economy of the State (Governor's Drought Task Force Irrigated Agriculture Work Group, 2004). Net farm income in Arizona was estimated at $1,399,446 in 2004, up from the five previous years. However, the number of farms in operation and the total acreage in farms has declined yearly since at least 1998 (Arizona Agricultural Statistics 2005).

Major field crops grown in the state include hay alfalfa, cotton, and wheat. These crops compose the vast majority of the value of field crop production in Arizona: approximately 88% in 2004. Arizona also produces a number of other field crops including corn, barley, and sorghum, but the value of production and acreage devoted to these crops is much less substantial. In addition to field crops, Arizona produces a number of vegetables (various varieties of lettuce and broccoli are the most dominant) as well as melons and potatoes. In western Arizona, vegetable production is typically rotated with field crops such as wheat and cotton. Alfalfa fields, however, are typically dedicated solely to the production of hay alfalfa (Nolte, 2006).

**Crop Acreage and Irrigation Water Use in Yuma and La Paz Counties**

Because dry-year transfers out of agriculture are voluntary and temporary, they maintain the viability of agriculture in the long run while meeting municipal and environmental water needs during drought. Counties along the Colorado River account for 88% of irrigated acreage in Arizona (Frisvold, 2004). Yuma and La Paz Counties were chosen as prospects for dry-year transfers because they produce a large quantity of relatively low-value crops using senior, mainstem Colorado River water. A majority of their irrigation withdrawals come from Colorado River water. Of the 875 million gallons/day (mgal/day) total irrigation withdrawals in La Paz County in 2000, 590 mgal/day were surface water (Hutson *et al.,* 2004). In Yuma County in 2000, surface water composed 1079 mgal/day of its total 1432 mgal/irrigation withdraw. 1.2 million acre-feet of Colorado River water are diverted annually in Yuma County (2001 Yuma County Agricultural Statistics). This represents over one-third of Arizona's total Colorado River allocation.

The warm, dry climate of La Paz and Yuma counties in southwestern Arizona, coupled with plentiful arable land and access to surface water from the Colorado River, create conditions for a successful agricultural sector in the region. La Paz County has 98,245 acres of cropland, of which 91,347 (93%) are irrigated (USDA- NASS 2002 Census of Agriculture). Yuma County contains 212,995 acres of cropland, with 197,424 (93%) irrigated acres. In 2002 there were 101 farms in La Paz County and 531 farms in Yuma County.

| Cropland in Study Area* | | | |
|---|---|---|---|
| | **ARIZONA** | **LA PAZ COUNTY** | **YUMA COUNTY** |
| **Number of Farms** | | | |
| 2002 | 7294 | 101 | 531 |
| 1997 | 8507 | 122 | 580 |
| **Total Cropland (Acres)** | | | |
| 2002 | 1261894 | 98245 | 212995 |
| 1997 | 1354820 | not available | 228758 |
| **Irrigated Cropland (Acres)** | | | |
| 2002 | 931735 | 91347 | 197424 |
| 1997 | 1075336 | 116985 | 207573 |

*Data from NASS 2002 Census of Agriculture

Table 1 Cropland Summary

The dominant field crops, in acreage, in both counties are alfalfa, upland cotton, and durum wheat. Production of these crops has either remained relatively steady or increased over the past five years. Cotton and wheat are typically rotated with vegetables (Nolte, 2006). Vegetable crops occupy less acreage than field crops but outweigh field crops in value of gross sales. Head lettuce is by far the most dominant vegetable produced in Arizona in terms of harvested acres, with almost all acreage concentrated in Yuma County.

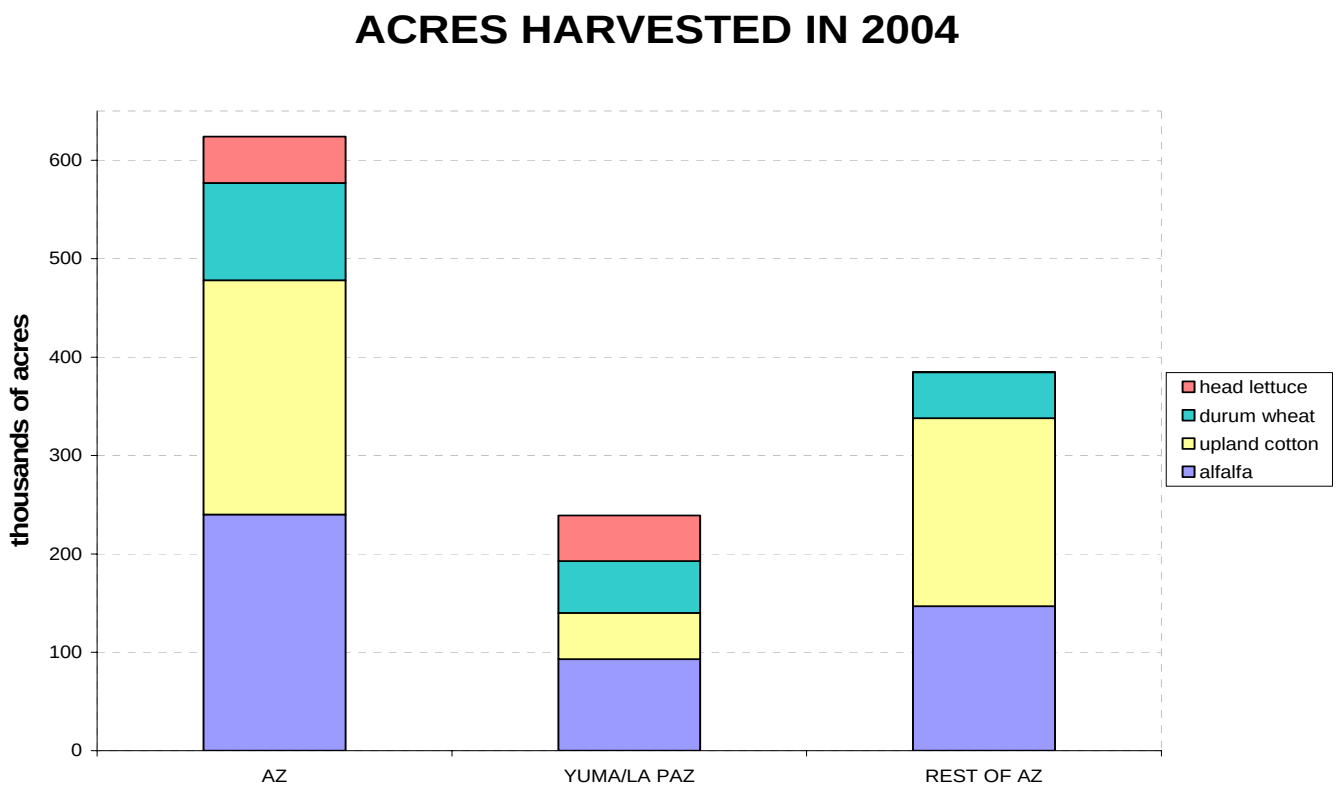



Figure 2 Summary of Harvested Acres, 2005 Arizona Agricultural Statistics Bulletin

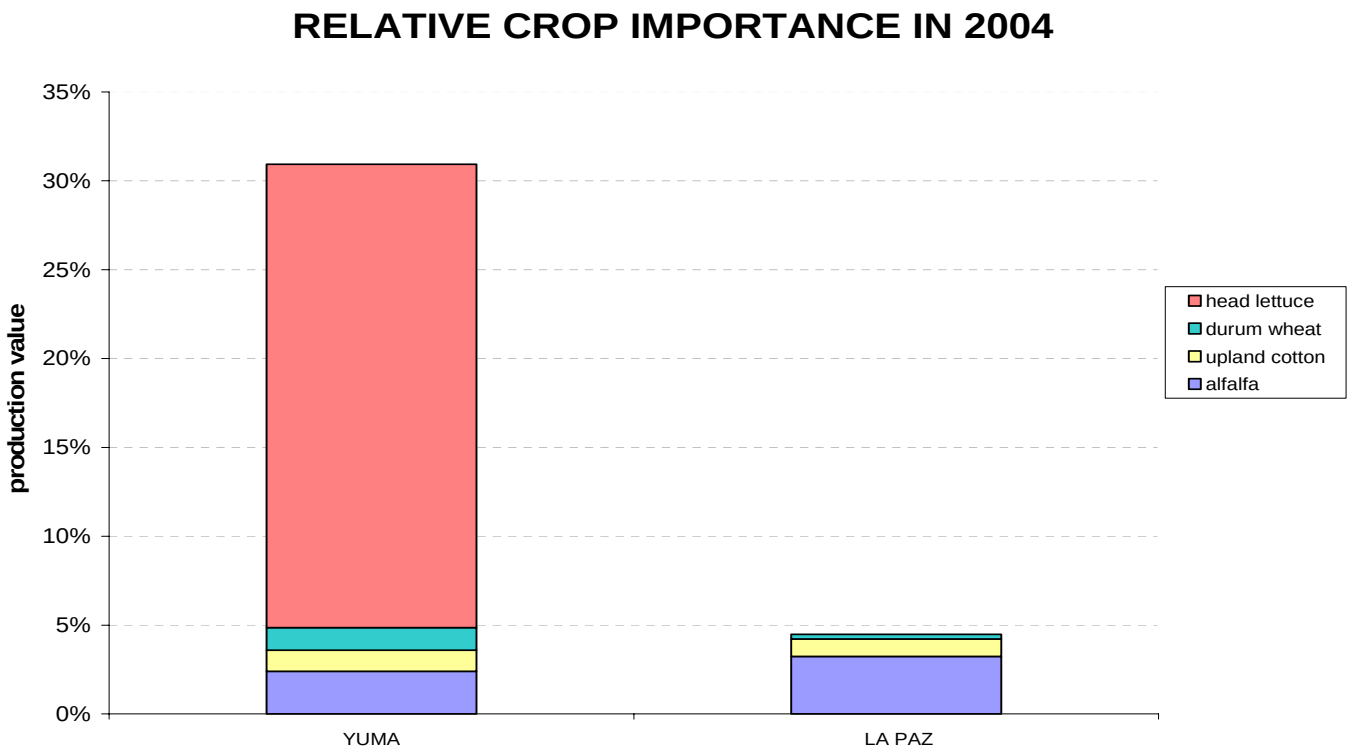



Figure 3 Percent of Arizona Crop Production Value, 2005 Arizona Agricultural Statistics Bulletin

Because dry-year forbearance programs can impact crop mix and crop rotations, head lettuce is also included in the crop budget for Yuma County. Due to its high net returns, lettuce is an unlikely candidate for irrigation forbearance, yet it needs to be considered as an important component of the seasonal crop mix. Other vegetable and fruit crops are also important. We focus on head lettuce here to illustrate issues forbearance programs may encounter with high-value crops.

The following tables illustrate the five-year movement (2000 to 2004) in the price and production for the field crops and head lettuces included in this analysis. Graphs visually depicting the five-year trend in acres planted, yield per acre, and price per unit are available in Appendix 2. Prices reported in the following two tables represent the market or spot value of the crops as reported by NASS. This price does not include federal farm program payments to producers.

## YUMA COUNTY - Five Year Trends

| **Hay Alfalfa** | **2000** | **2001** | **2002** | **2003** | **2004** | **AVG** |
|---|---|---|---|---|---|---|
| Acres Planted | NA | NA | NA | NA | NA | NA |
| Acres Harvested | 30000 | 31500 | 32000 | 31000 | 28000 | 30500 |
| Yield per Acre (tons) | 8.67 | 8.25 | 8.62 | 9.68 | 10 | 9.044 |
| Production (tons) | 260000 | 260000 | 275700 | 300000 | 280000 | 275140 |
| Price per Ton | $94.00 | $99.00 | $100.00 | $89.50 | $99.50 | $96.40 |
| Value of Production | $24,440,000 | $25,740,000 | $27,570,000 | $26,850,000 | $27,860,000 | $26,492,000 |
| **Cotton, Upland** | **2000** | **2001** | **2002** | **2003** | **2004** | **AVG** |
| Acres Planted | 25400 | 26000 | 18200 | 24600 | 26800 | 24200 |
| Acres Harvested | 25300 | 25500 | 17900 | 24500 | 26700 | 23980 |
| Yield per Acre (pounds) | 1385 | 1129 | 1397 | 1254 | 1438 | 1320.6 |
| Production (bales) | 73000 | 60000 | 52100 | 64000 | 80000 | 65820 |
| **Price per Pound | $0.40 | $0.28 | $0.46 | $0.66 | $0.44 | $0.45 |
| Value of Production | $13,911,079 | $8,176,218 | $11,577,917 | $20,400,072 | $17,047,202 | $14,222,498 |
| **Wheat, Durum** | **2000** | **2001** | **2002** | **2003** | **2004** | **AVG** |
| Acres Planted | 38600 | 36800 | 44300 | 46000 | 43000 | 41740 |
| Acres Harvested | 38600 | 36400 | 44300 | 46000 | 42500 | 41560 |
| Yield per Acre (bushels) | 101.7 | 95.8 | 96.5 | 102.7 | 100 | 99.3 |
| Production (bushels) | 3923000 | 3488333.333 | 4272000 | 4724666.667 | 4250000 | 4131600 |
| Price per Bushel | $3.50 | $3.95 | $4.40 | $4.65 | $4.25 | $4.15 |
| Value of Production | $13,734,423 | $13,782,405 | $18,801,072 | $21,969,700 | $18,066,750 | $17,270,870 |
| **Lettuce, Head** | **2000** | **2001** | **2002** | **2003** | **2004** | **AVG** |
| Acres Planted | 50300 | 52000 | 51000 | 50000 | 47000 | 50060 |
| Acres Harvested | 50300 | 51800 | 50000 | 49600 | 46500 | 49640 |
| Yield per Acre (cwt) | 350 | 365 | 350 | 360 | 360 | 357 |
| Production (thousand cwt) | 17605 | 18907 | 17500 | 17856 | 16740 | 17721.6 |
| Price per cwt | $13.10 | $16.50 | $38.70 | $10.30 | $22.20 | $20.16 |
| Value of Production | $230,625,500 | $311,965,500 | $677,250,000 | $183,916,800 | $371,628,000 | $355,077,160 |

*Source: National Agricultural Statistics Service 2005 & 2004 Arizona Agricultural Statistics Bulletin

**Market price received by growers

Table 2 Yuma 5-Year Trends

| LA PAZ COUNTY - Five Year Trends | | | | | | |
|---|---|---|---|---|---|---|
| **Hay Alfalfa** | **2000** | **2001** | **2002** | **2003** | **2004** | **AVG** |
| Acres Planted | NA | NA | NA | NA | NA | NA |
| Acres Harvested | 59000 | 61100 | 63000 | 61000 | 65000 | 61820 |
| Yield per Acre (tons) | 8.47 | 8.38 | 7.94 | 8.03 | 6.92 | 7.948 |
| Production (tons) | 500000 | 512000 | 500000 | 490000 | 450000 | 490400 |
| Price per Ton | $94.00 | $99.00 | $100.00 | $89.50 | $99.50 | $96.40 |
| Value of Production | $47,000,000 | $50,688,000 | $50,000,000 | $43,855,000 | $44,775,000 | $47,263,600.00 |
| **Cotton, Upland** | **2000** | **2001** | **2002** | **2003** | **2004** | **AVG** |
| Acres Planted | 18000 | 17500 | 12200 | 16100 | 20500 | 16860 |
| Acres Harvested | 17900 | 17000 | 12000 | 16000 | 20400 | 16660 |
| Yield per Acre (pounds) | 1378 | 1200 | 1248 | 1350 | 1553 | 1345.8 |
| Production (bales) | 51400 | 42500 | 31200 | 45000 | 66000 | 47220 |
| **Price per Pound | $0.40 | $0.28 | $0.46 | $0.66 | $0.44 | $0.45 |
| Value of Production | $9,792,481 | $5,793,600 | $6,933,888 | $14,342,400 | $14,066,453 | $10,185,764 |
| **Wheat, Durum** | **2000** | **2001** | **2002** | **2003** | **2004** | **AVG** |
| Acres Planted | 6500 | 5100 | 5600 | 8000 | 10000 | 7040 |
| Acres Harvested | 6500 | 5100 | 5600 | 8000 | 10000 | 7040 |
| Yield per Acre (bushels) | 94.7 | 96.2 | 92.7 | 101.3 | 88.0 | 94.6 |
| Production (bushels) | 615000 | 490666.6667 | 519000 | 810000 | 880000 | 662933.3333 |
| Price per Bushel | $3.50 | $3.95 | $4.40 | $4.65 | $4.25 | $4.15 |
| Value of Production | $2,153,115 | $1,938,624 | $2,284,119 | $3,766,500 | $3,740,880 | $2,776,647.60 |

*Source: National Agricultural Statistics Service 2005 & 2004 Arizona Agricultural Statistics Bulletin

**Market price received by growers

Table 3 La Paz 5-Year Trends

### Data and Procedures for Calculating Net Returns To Irrigation Water Use

The first step in crop-budget analysis is to obtain data on the steps in the production process, timing, required production resources, and resulting outputs from a crop- and location- specific crop budget. This study used the county crop budgets developed by the University of Arizona Department of Agricultural and Resource Economics (Teegerstrom *et al.,* 2001; Teegerstrom and Knowles, 1999; Teegerstrom and Ticks, 1999) as a model. The most recent published farm budgets (1999/2001) were substantially updated in the course of this research to reflect current crop yields and prices, chemical application rates, typical production operations, and fuel and labor costs. Updated crop yields and prices were obtained from USDA-NASS. Up-to-date seed prices were quoted and averaged from several seed companies located in Yuma and La Paz counties (H&H Seed Co, 2006; Barkley Seed Inc., 2006; Carr Seed Co., 2006). Current chemical prices were quoted from Fertizona, an agricultural chemical dealer in Arizona (Osborn, 2005; Osborn, Feb. 2006; Osborn, April 2006). Chemical application rates were updated to reflect current practices. These application rates were provided by a University of Arizona Agricultural Extension Officer for Yuma County (Nolte, 2005). It should be noted that chemical application rates for head lettuce were not available at the time this

research was concluded, thus application rates used in calculations of NROVC for head lettuce are based on information from 2001.

Agricultural extension agents also provided information about changes in standard production operations since the last farm budgets were published (Nolte, 2006). Estimates of current fuel costs for agricultural use were supplied by several gas companies in each county and averaged (Parker Oil, 2006; Amerigas, 2006; Union Oil, 2006; Ferrel Gas, 2006). Labor costs were abstracted from the 2004 Arizona Agricultural Statistical Bulletin (Arizona Agricultural Statistics, 2005). Appendix Two provides detailed variable cost calculations, exclusive of water costs, for each location-specific crop in this analysis.

Because federal farm support payment can substantially improve the profitability of certain crops in certain locations, this analysis also includes loan deficiency payments (LDP) in calculations of returns (Center for Agricultural and Rural Development, 2005). In Arizona, the LDP payment is currently only applicable to cotton. Other federal payments, in particular counter-cyclical payments and direct payments, are de-coupled from crop production. Consequently receipt of these payments would not be affected by irrigation forbearance (Reinertson, 2006) though such payments influence overall farm profitability.

Unit Crop Budget is assembled and used to calculate net returns over variable costs (NROVC) per acre for each crop. NROVC estimates the on-farm economic value of water in crop production and is calculated by subtracting variable production costs (exclusive of water costs) from gross returns per acre. In other words, the residual from the difference between the gross value of crop production and non-water input is attributed to be the return to irrigation water in crop production (Naeser and Bennett, 1998). This value is the maximum value an irrigator could pay for water and still cover the variable costs of production. This value can also be translated into NROVC per acre-foot of water applied to a specific crop. The method described above is a reasonable approach to estimate the short-run value of irrigation water since only variable costs of production are accounted for. Fixed costs are not a chief consideration in yearly production decisions (Naeser and Bennett, 1998). A longer-run estimate of the on-farm value of irrigation water, however, would require the inclusion of the fixed costs of production. Moreover, attributing all of the NROVC to the water input ***overstates*** the on-farm economic value of irrigation water because farm budget data do not assign a cost per acre for management expertise and farm assets such as equipment.

## Net Returns By County and Crop

The table below illustrates calculation of NROVC for cotton in Yuma County based on differing scenarios for crop prices and yields. These include five-year highs for both price and yield (High), five-year lows for both (Low), five-year averages for price and yield (2000 – 2004), and actual 2004 crop prices and yields per acre. Similar tables for other crops included in this analysis can be found in Appendix Three.

| Yuma Upland Cotton | 2004 | 5yr Avg | High | Low |
|---|---|---|---|---|
| **Revenue per Acre** | | | | |
| Yield/acre (lint) | 1438 | 1320.6 | 1438 | 1129 |
| Price/unit (lint) | 0.5 | 0.4616 | 0.664 | 0.284 |
| Yield/acre (seed) | 1.24 | 1.06 | 1.24 | 0.87 |
| Price/unit (seed) | 160 | 139.2 | 160 | 124 |
| LDP/Marketing Gain Rate | 0.149 | 0.143 | 0.076 | 0.28 |
| Price Plus LDP per unit | 0.649 | 0.6046 | 0.74 | 0.564 |
| Gross Revenue ($/Acre) | 1131.662 | 945.98676 | 1262.52 | 744.636 |
| **Total Variable Costs per Acre** | 1194.37 | 1194.37 | 1194.37 | 1194.37 |
| **Net Returns Over Variable Costs Per Acre** | -62.708 | -248.38324 | 68.15 | -449.734 |
| A/F of water applied per acre | 4.2 | 4.2 | 4.2 | 4.2 |
| **Net Returns Over Variable Costs Per Acre-foot of water applied** | -14.93 | -59.14 | 16.23 | -107.08 |

Table 4 NROVC, Upland Cotton. See Appendix Three for detailed citation.

NROVC for production of upland cotton in Yuma County is negative, except for the scenario that assumes five-year highs for both price and yield. The NROVC calculations do not, however, include federal price support payments that cotton producers receive in addition to the market price and the loan deficiency payment. These payments are not included because a grower's decision to cease irrigation does not affect their receipt (Reinertson, 2006). Thus, even if a grower refrains from irrigation for a season to lease out their water, they will still receive these payments and these federal programs do not affect calculations of NROVC.

The following tables summarize full-season NROVC/acre and NROVC/AF for all crops analyzed in Yuma and La Paz using the five-year average price per unit and yield per acre.

**YUMA COUNTY NROVC**

| CROP | NROVC/ACRE | AF WATER/ACRE | NROVC/AF |
|---|---|---|---|
| Alfalfa | $365.03 | 5.8 | $62.94 |
| Durum Wheat | -$29.78 | 3.5 | -$8.51 |
| Upland Cotton | -$248.38 | 4.2 | -$59.14 |
| Head Lettuce | $3823.56 | 3.6 | $1062.10 |

Table 5 NROVC, Yuma Crops

| LA PAZ COUNTY NROVC | | | |
|---|---|---|---|
| **CROP** | **NROVC/ACRE** | **AF WATER/ACRE** | **NROVC/AF** |
| Alfalfa | $398.10 | 5.8 | $68.64 |
| Durum Wheat | $99.53 | 3.5 | $28.44 |
| Upland Cotton | -$111.74 | 4.2 | -$26.60 |

Table 6 NROVC, La Paz Crops

NROVC provide an objective baseline to inform negotiations over dry-year forbearance payments. The exercise payment in a voluntary program could not lie below NROVC for a specific crop, since in that case the farmer would be better off producing crops. Exercise payments may be larger than NROVC to provide an incentive for farmers to participate in a forbearance program and to cover other costs. On the other hand, a grower weighing various risks of crop production and marketing may choose a certain forbearance payment over an uncertain net return to crop production.

**Issues Related to Higher and Lower Value Crops**

The calculation of NROVC in Yuma and La Paz counties expose two important issues. First, the negative NROVC of upland cotton and durum wheat in Yuma County and upland cotton in La Paz County suggests a potential for significant financial benefits for producers who participate in dry-year options arrangements instead of irrigating these specific crops. Second, the high value of NROVC for head lettuce highlights the point that cost effective dry-year option arrangements must be structured so that low-value crops can temporarily be taken out of production while seasonal high-value vegetables continue to be produced. In western Arizona, vegetables are typically planted in November and harvested through March, after which time irrigators switch to production of field crops for late spring and summer months (Nolte, 2006). Because the timing of vegetable harvest may not coincide with the need for leased water, however, options agreements need to be carefully and creatively structured to focus on fallowing low-value crops.

In reviewing and comparing the NROVC for crops in Yuma and La Paz counties, the question naturally arises as to why growers do not plant more acreage in high return specialty crops such as lettuce. Suppliers of head lettuce in the U.S. are almost exclusively in Arizona and California, respectively representing 26% and 73% of national production in 2004 (Boriss and Brunke, 2005). In Arizona, head lettuce production is carefully timed so that harvest dates coincide with the times of the year when the harvest of head lettuce in California is low, typically in November and December and again in late March and into April. These harvest dates also take advantage of the micro-climates in California and Arizona that are most conducive to high-quality head lettuce production (Teegerstrom, 2006). Successfully entering the head lettuce market requires extensive planning and well established marketing networks (Teegerstrom, 2006). For any chance of financial success, the decision to produce and sell head lettuce cannot be made without careful forethought.

Though the potential returns are high, head lettuce production is extremely high risk and capital intensive. The market for lettuce is unstable with respect to price received by producers and is locally, not globally, driven (Kerns *et al.*, 1999). Unlike other field crops, lettuce cannot be stored and sold when market prices are high. Its perishable nature means lettuce is sold immediately after harvest, and if market conditions are not favorable at the time of harvest, a grower has no choice but to accept the low prices or plow under the lettuce that cannot be profitably sold.

The market price of lettuce has historically been volatile and is particularly sensitive to changes in supply. Flooding and disease or insect outbreaks, for instance, can dramatically reduce supply and correspondingly boost the market price. If there is surplus supply, however, the market price will plummet and only the highest quality heads (without insect damage or contamination) will be accepted by packers (Kerns *et al.*, 1999). And because growers cannot reliably predict what supply conditions will prevail during harvest, they must consistently incur the added costs of ensuring only the highest quality production.

The following two graphs depict the volatile nature of market prices for head lettuce. The first graph shows average seasonal market prices received by growers in Arizona between 1980 and 2004. The second graph shows the weekly fluctuation in prices received by Arizona growers for the first six months of 2006. Price fluctuations occur due to weather and other factors affecting yield and harvest dates in the numerous lettuce growing microclimates.

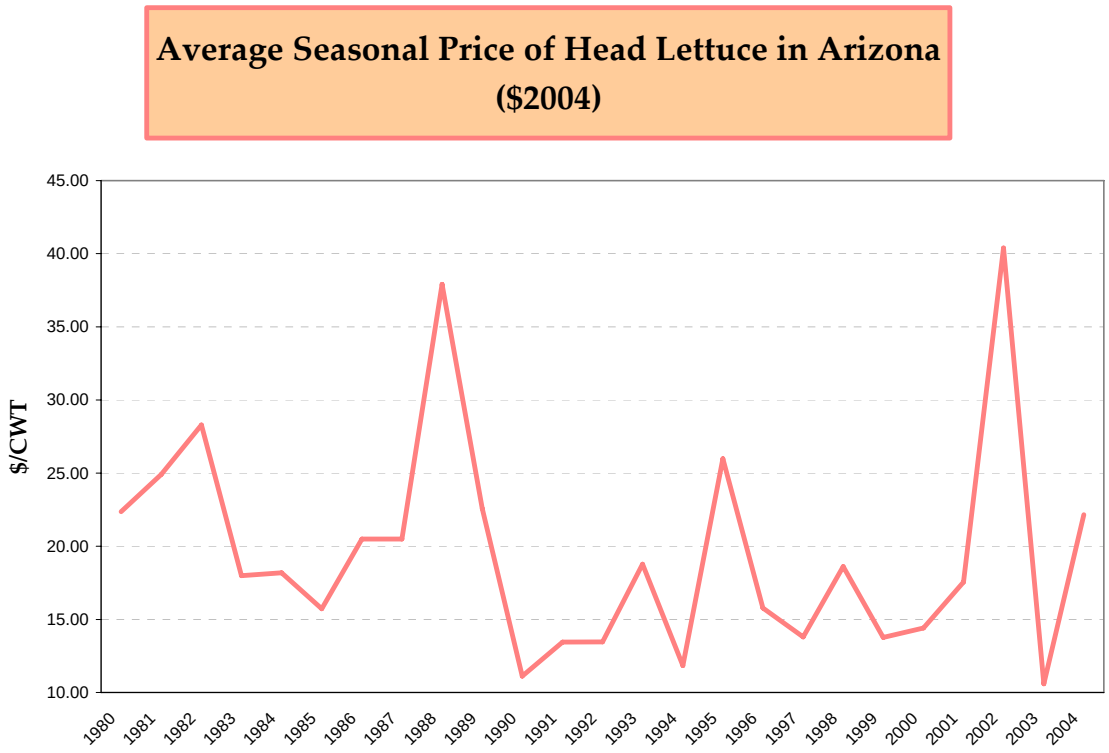



Table 7 Seasonal Price of Head Lettuce

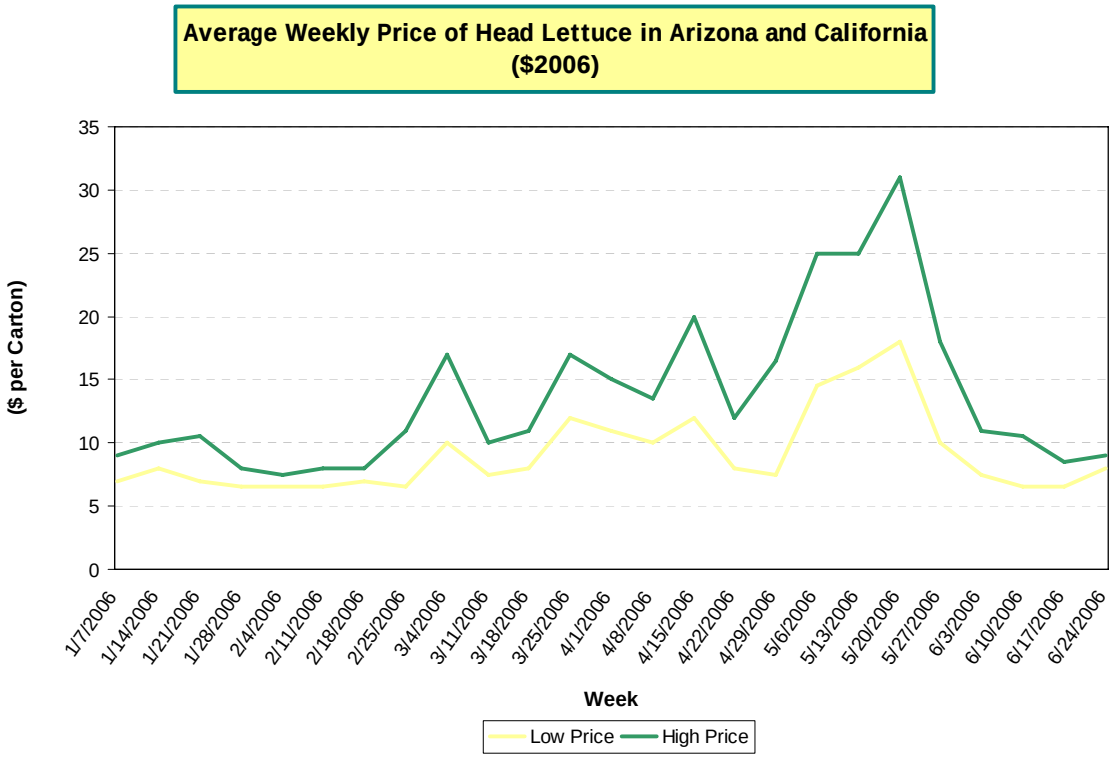



Table 8 Average Weekly Price of Head Lettuce, 2006 season. Note: Jan through mid-April is primarily western Arizona harvest, and late April through June is primarily California harvest.

In making production decisions, growers consider not only the potential profitability of a crop but also the input costs and risks inherent in production and marketing of that crop. The variable costs of production for head lettuce and other vegetables are very high compared to field crops. A farmer who has the necessary networks in place and decides to incur the high production costs associated with head lettuce production, also is taking the risk of volatile, unpredictable market conditions. If the market price for head lettuce is low when the crop is harvested, the grower must choose between accepting those prices or plowing under the crop (thus averting harvest costs) and will likely incur a large financial loss for the season on his lettuce acreage.

**Seasonal Considerations in Structuring Forbearance Programs**

The time of year when growers are asked to cease irrigation has implications for compensation payments. In some instances, growers will have already produced some crop (and earned revenues) and may have also already incurred some of the variable costs of production. To accurately account for the value of foregone crop production, the timing of forbearance must be taken into account. Tables in Appendix Four provide a monthly accounting of the variable costs of production for major crops in Yuma and La Paz Counties.

Using these tables, forbearance payments can be tied to the time of year an option is exercised. If, for example, an option is exercised before November for the upcoming season, a Yuma County cotton producer would not yet have incurred variable costs associated with cotton production, and thus the baseline calculation of NROVC for upland cotton would apply. If, however, irrigators are asked to cease irrigating late in the growing season (i.e. after July 30), they will have already incurred almost 57% of their variable costs without having produced a marketable crop, so approximately $677 arguably could be added on to minimum compensation per acre, substantially increasing the cost of the forbearance arrangement. (See tables in Appendix Four).

Unlike cotton and wheat, alfalfa production in western Arizona is a year-round process, and harvesting occurs regularly (approx. every three weeks) throughout the months of April to October and once a month from November to January (Nolte, 2006). As a result, NROVC in alfalfa are affected by the time of year a grower is asked to cease irrigating his crop based on variable costs already incurred, and also based on alfalfa already harvested.

The production of other field crops, however, is seasonal. Growers in western Arizona typically mix field crop production with vegetable production within the same year (Nolte, 2006). Durum wheat is planted in December and harvested in June. This is followed by the planting of vegetables, often either head lettuce, cauliflower, or broccoli. Land preparation for upland cotton begins in December. The cotton is typically planted in March and then harvested in August. Like wheat, cotton harvesting is followed by vegetable planting.

The time of year when a forbearance option is exercised has significant consequences for the on-farm net returns foregone and forbearance program costs. NROVC for head lettuce production, for example,

are very high relative to field crops. If forbearance programs interrupt the production of lettuce (or other high value specialty crops), payments to growers would necessarily be substantially higher to account for the foregone profit of lettuce production.

The most cost effective scenario for irrigation forbearance on cropland planted in a field crop/vegetable annual crop mix is to request participating growers to forbear irrigation in the late spring and summer (forbearing production of field crops), and then provide water for production of vegetables in the winter or spring. These seasonal arrangements reduce the foregone net returns in crop production, but may also require water storage arrangements to match timing of irrigation cessation with seasonal need for additional water by municipalities or fish and wildlife programs. If, however, climate and water supply prediction tools can be used to anticipate the timing and magnitude of need for additional water in upcoming months or years, then forbearance options can be exercised for field crops and the conserved water could be banked by the lessee for use later in the year. This strategy rests on two assumptions: (1) the capacity to predict water supply shortfalls in December-February is accurate enough to inform negotiations over the structure and pricing of forbearance agreements that might be exercised the following summer (a short term, one-time option contract) and/or prediction capacity is accurate enough to inform longer term option contracts intended to assure supply reliability for 20-50 years (long term contract); (2) adequate storage capacity is available at reasonable cost to carry the unused irrigation water into future seasons and years for use by those contracting for forbearance.

## Further On-Farm Financial Considerations

In assessing the value of water in crop production, there are a few additional factors that should be considered. The first is the effect of irrigation forbearance on federal price support payments. In particular, the value of foregone crop production could change if counter-cyclical payments (tied to the market price of cotton), and direct payments become affected by temporary irrigation forbearance. According to County Executive Director of the Yuma and La Paz Counties Arizona Farm Services Agency, these decoupled federal payments currently would not be affected by a farmer's decision to temporarily cease irrigation (Reinerston, 2006). The farmer would, however, still be responsible for managing noxious weeds on the fallowed lands.

Another consideration is crop insurance. Farmers can purchase yield-based insurance, known as Actual Production History, which insures producers against yield losses due to natural causes such as drought, flooding, hail, wind, frost, insects, and disease (USDA 2005). An individual farmer selects the percent of average yield to be insured (50-75%) as well as the percent of predicted price to be insured (55-100%). They can also purchase revenue-based insurance, called Crop Revenue Coverage, which provides revenue protection based on price and yield expectations. Farmers who purchase crop insurance also receive a premium "subsidy payment" (USDA, 2006; Babcock and Hart, 2005). According to University of Arizona Extension Economist Russell Tronstad, farmers who cease irrigating their cropland are not entitled to crop insurance on the acres involved in forbearance for that year (Tronstad, May 1, 2006). The foregone

insurance subsidy payment, as well as potential crop insurance payments, cannot readily be factored into NROVC calculations as they do not vary predictably with crop yield. While they could influence a farmer's decision to participate in a forbearance program, many Arizona growers do not purchase crop insurance because almost all crop production is irrigated, so the yield risk is lower than for dryland farming operations (Tronstad, May11, 2006).

A final important consideration is the role of fixed costs of production. Growers may negotiate to include some fixed costs of production in payments received to refrain from irrigating. A rationale for including some fixed costs is to maintain the economic vitality of the overall farm operation, which cannot survive indefinitely if only variable costs of production are covered.

This research examines average crop production conditions for Yuma and La Paz Counties in the University of Arizona Crop Budget framework. Many factors that influence the cost of production as well as yields and gross returns vary widely within a county. For instance, crop yields differ somewhat across soil types in Yuma and La Paz counties. Also, the type of irrigation system a farmer uses and management time and skill impacts the per acre application rate of water. Additionally, the production operations, chemicals applied and their application rates, etc., can all vary from farm to farm within the same county. Finally, the residual valuation method is sensitive to input and output prices. Wherever possible, input and output prices used in this research were updated to reflect the most recent information available. However, many of these prices fluctuate over time and the NROVC results presented in this report should be treated as *estimates* generalized to the county level. NROVC is a straightforward calculation and, following the basic procedures applied here, can readily be modified and updated to fit the specific production and market conditions faced by a particular group of growers.

## CONCLUSIONS

The vast majority of consumptive water use in the Lower Colorado River Basin occurs in irrigated agriculture. When drought conditions threaten to impose high costs in other sectors, voluntary irrigation forbearance can be a means to mitigate regional drought impacts. Irrigators and irrigation districts have access to some of the most senior water in the Lower Basin, while municipalities and other CAP users in Arizona are far more susceptible to dry-year shortfalls.

Voluntary dry-year water leases are particularly conducive to minimizing drought-induced water supply variability. This research highlights promising mechanisms to enhance dry-year supply reliability and reduce regional drought impacts in the Lower Basin. These temporary, drought-triggered transfers out of agriculture for municipal or environmental use are especially appropriate to facilitate reallocation in the Lower Basin given the region's vast irrigated agricultural base coupled with burgeoning populations and urban development.

A critical component of structuring and negotiating dry-year transfers is determining the appropriate exercise payment, the compensation growers receives if the option is exercised and they cease irrigating a specific amount of cropland. This research uses the residual (farm budget) approach to determine net returns

over variable costs for alfalfa, upland cotton, and durum wheat production in Yuma and La Paz counties in western Arizona. This calculation can be useful as a baseline in negotiating exercise payments.

The results indicate that, based on five-year average crop yields and prices, the payment a grower would need to be offered to be just as well off as if they had irrigated is $365.03/acre (or $62.94/AF of water applied) for alfalfa in Yuma County. NROVC for wheat and cotton are both negative in Yuma, suggesting that payments to forbear irrigating these crops are likely to be of interest to growers, as a forbearance payment leaves a grower financially better off than they would have been producing the crops. In La Paz County, NROVC estimates suggest an exercise payment of at least $398.10/acre ($68.64/AF of water applied) for alfalfa, $99.53/acre ($28.44/AF of water applied) for durum wheat, and simply a positive exercise payment for upland cotton. NROVC for head lettuce, the only vegetable included in this analysis, are significantly higher than any of the field crops. NROVC for head lettuces are estimated at $3,823.56/acre or $1,062.10/AF of water applied. However, the residual method used to calculate NROVC does not provide an accurate estimate of the on-farm value of irrigation water for high-value crops like lettuce. The costs that are not accounted for in NROVC are particularly high for these types of crops. Special management skill, complex marketing negotiations and a high acceptance of risk are necessary to be successful. Since monetary costs are not readily available for these traits, the residual method overestimates water's value (Young, 2005).

Results from the farm budget analysis highlight the importance of timing in accurately establishing a baseline for exercise payment negotiations. If growers are asked to refrain from irrigating before field crop production begins, compensating them to the level that would leave them just as well off had they irrigated is much less costly than asking them to cease irrigation later in the season when they have already incurred some variable costs of production. Foregone crop revenue is also substantially higher if forbearance programs interrupt vegetable production, so creativity and care are necessary in structuring forbearance agreements in the most cost effective way possible.

The precarious balance of water supply and demand in the Lower Colorado River Basin leaves CAP water users particularly susceptible to drought-induced supply variability. The economic, environmental, and social costs associated with variable supply are diverse and can be far reaching. Particularly in dry years, temporary water transfers are a viable mechanism to enhance supply reliability and help mitigate the negative effects of drought.

Dry-year transfers provide important advantage over permanent acquisitions for all parties to the arrangement. Irrigators use their water for its customary purposes during years when the demand for temporary leases is low and can benefit financially by leasing their water in dry years. Dry-year transfers also provide cities and habitat restoration programs the flexibility to lease water only when supply augmentation is necessary. Instead of incurring the economic and political costs of purchasing permanent water rights, temporary transfers allow for year to year decisions about leasing additional water. Further, by

maintaining the ownership of the water right with the original user, third-party impacts and transaction costs can be minimized.

In general, temporary dry-year transfers are more expensive on a per acre-foot per year basis than the outright purchase of water rights. The higher cost must therefore be justified by a significant improvement in dry-year supply reliability, and by lower third party impacts and political opposition (as compared to permanent acquisitions). Forbearance programs must be carefully structured to maximize supply reliability benefits, to focus on fallowing lower valued crops and to accept reliable "wet water" sources and reject "paper water."

In sum, effective voluntary dry-year lease programs require careful structuring, but if well planned, can decrease the pressure for permanent water transfers out of agriculture. Typically, senior consumptive users such as irrigators and Native American tribes have the most reliable water in a region that could firm supplies for other users by temporary irrigation forbearance. While the third party impacts generated by temporary transfers are lower than with permanent purchases, local economic impacts still must be systematically addressed.

Addressing potential drought shortages is not simple or inexpensive, but pre-planning is more effective and less costly than reactive, crisis management responses to drought. Water in the West creates an "inextricable web of mutuality" between rural and urban users and at the tribal, municipal, state, and federal levels. Tackling supply reliability necessitates integrated participation and acceptance of reliability enhancement strategies from all parties involved. Despite the costs, complexities and collaborative efforts required, temporary irrigation forbearance could well spare the Lower Colorado River Basin from significant economic losses in sectors lacking reliable supplies during severe drought.

## REFERENCES CITED


Amerigas Propane, Parker, Arizona. Telephone interview. Jan. 2006.

Arizona Agricultural Statistics. "2005 Arizona Agricultural Statistical Bulletin." Sept. 2006. Phoenix, AZ.

Arizona Agricultural Statistics. "2004 Arizona Agricultural Statistical Bulletin." Sept. 2005. Phoenix, AZ.

Arizona Agricultural Statistics. "2002 Arizona Agricultural Statistical Bulletin." 2003. Phoenix, AZ. http://www.nass.usda.gov/Statistics_by_State/Arizona/Publications/Annual_Statistical_Bulletin/02bul/main.htm.

Arizona Water Banking Authority. "Executive Summary." http://www.awba.state.az.us/backgrnd/exec_sum.html.

Babcock, Bruce A. and Chad E. Hart. "Influence of the Premium Subsidy on Farmers' Crop Insurance Coverage Decisions." Center for Agricultural and Rural Development, Iowa State University. April 2005. http://www.card.iastate.edu/publications/DBS/PDFFiles/05wp393.pdf.

Barkley Seed Inc., Yuma, Arizona. Telephone interview. 6 Feb. 2006.

Boriss, Hayley and Henrich Brunke. "Commodity Profile: Head Lettuce." Agricultural Issues Center. University of California. 2005. http://aic.ucdavis.edu/profiles/lettuce-2005.pdf.

Brookshire, David S., Bonnie Colby, Mary Ewers, and Philip T. Ganderton. "Market prices for water in the semiarid West of the United States." *Water Resources Research.* (2004) 40. W09S01. doi:10.1029/2004WR003394.

Brozovic, Nicholas, Janis M. Carey, and David L. Sunding. "Trading Activity in an Informal Agricultural Water Market: An Example from California." *Water Resources Update.* 121(2002): 3-16.

Bureau of Reclamation. "Development of Lower Basin Shortage Guidelines and Coordinated Management Strategies for Lake Powell and Lake Mead Under Low Reservoir Conditions." Oct. 2005. http://www.usbr.gov/lc/region/g4000/strategies/factsheet.pdf.

Bureau of Reclamation. "Bypass Flow Replacement or Recovery Methods Alternatives." Dec. 2005. http://www.usbr.gov/lc/region/programs/bypass/alternatives.html#forbear.

Bureau of Reclamation. "Development of Lower Basin Shortage Guidelines and Coordinated Management Strategies for Lake Powell and Lake Mead, Particularly Under Low Reservoir Conditions." March 2006a. http://www.usbr.gov/lc/region/programs/strategies.html.

Bureau of Reclamation. "Scoping Summary Report: Development of Lower Basin Shortage Guidelines and Coordinated Management Strategies for Lake Powell and Lake Mead, Particularly Under Low Reservoir Conditions." March 2006b. http://www.usbr.gov/lc/region/programs/strategies/scopingreport/report.pdf.

Bureau of Reclamation. "Lake Powell – Glenn Canyon Dam – Current Status." April 2006. http://www.usbr.gov/uc/water/crsp/cs/gcd.html.

Bureau of Reclamation. "Seven Basin States' Preliminary Proposal Regarding Colorado River Interim Operations." Feb 2006. http://www.usbr.gov/lc/region/programs/strategies/consultation/Feb06SevenBasinStatesPreliminaryProposal.pdf.

Carr Seed Company, Yuma, Arizona. Telephone interview. 6 Feb. 2006.

Center for Agricultural and Rural Development. Iowa State University. 2005. http://cardsrv7.card.iastate.edu/LDPHome.aspx.

Checchio, Elizabeth. "Water Farming: The Promise and Problems of Water Transfers in Arizona", Department of Hydrology and Water Resources, University of Arizona. 1988.

*Conservation Before Shortage: Proposed Shortage Criteria for Colorado River Operations.* July, 2005. http://www.environmentaldefense.org/documents/4601_CBSshortageproposal2.pdf.

Clifford, Peggy, Clay Landry, and Andrea Larsen-Hayden. "Analysis of Water Banks in the Western States." July 2004. Prepared by Washington State Department of Ecology and WestWater Research.

Ferrel Gas, Yuma, Arizona . Telephone interview. Jan. 2006.

Frisvold, George. University of Arizona Agricultural and Resource Economic Professor. Email Communication. June 1, 2005.

Gollehon, Noel R. "Water Markets: Implications for Rural Areas of the West." *Rural Development Perspectives.* 14.2(1999): 57-63.

Gollehon, Noel, and William Quinby. "Irrigation in the American West: Area, Water and Economic Activity." *Water Resource Development.* 16.2(2000): 187-195.

Governor's Drought Task Force Irrigated Agriculture Work Group. Sept. 28, 2004.

Gibbons, D.C. *The Economic Value of Water.* Washington D.C.: Resources for the Future, Inc., 1986.

Griffin, Ronald C. *Water Resource Economics: The Analysis of Scarcity, Policies, and Projects.* Cambridge, MA: The MIT Press, 2006.

H & H Seed Company, Yuma, Arizona. Telephone interview. 6 Feb. 2006.

Harding, Benjamin L., Taiye B. Harding, and Elizabeth A. Payton. "Impacts of a Severe Sustained Drought on Colorado River Water Resources." *Water Resources Bulletin* (Oct. 1995): 815-824.

Howe, Charles W., Lynne Bennett, Charles M. Brendecke, J. Ernest Flack, Robert M. Hamm, Roger Mann, Lee Rozaklis, Mark Griffin Smith, and Karl Wunderlich. "Urban Water Supply Reliability: Preferences of Managers, Elected Officials and Water Users in Boulder, Colorado." Colorado Water Resources Research Institute. December, 1990. cwrri.colostate.edu/pubs/series/completionreport/complete%20CR%20158.pdf.

Howitt, Richard E. "Spot Prices, Option Prices, and Water Markets: An Analysis of Emerging Markets in California." *Markets for Water: Potential and Performance*. Eds. Easter, K.W., Rosegrant, M., Dinar. Kluwer Academic Publishers: New York, 1998.

Howitt, Richard E. "The Economic Impact of Water Transfers on Alfalfa in the West." Proceedings, Western Alfalfa and Forage Conference, 11-13 December, 2002, Sparks, NV, UC Cooperative Extension. ucanr.org/alf_symp/2002/02-031.pdf.

Howitt, Richard E. and Ellen Hanak. "Incremental Water Market Development: The California Water Sector 1985-2004." *Canadian Water Resource Journal.* 30.1(2005): 73-82.

Howitt, Richard and Kristiana Hansen. "The Evolving Western Water Markets." *Choices Magazine.* 20.1(2005).

Keplinger, Keith O., and Bruce McCarl. "An Evaluation of the 1997 Edwards Aquifer Irrigation Suspension." *Journal of the American Water Resources Association.* 36.4(2000): 889-901.

Kerns, David, Michael Marheron, John Palumbo, Charles Sanchez, David W. Still, Barry Tickes, Kai Umeda, and Mark Wilcox. "Guidelines for Head Lettuce Production in Arizona." IPM Series, Number 12. 1999. http://ag.arizona.edu/pubs/crops/az1099/.

Landry, Clay J., and Terry L. Anderson. "The Rising Tide of Water Markets." ITT Industries Guidebook to Global Water Issues. 1999. http://www.itt.com/waterbook/page71.pdf.

Loomis, J., K. Quattlebaum, T.C. Brown, and S.J. Alexander. "Expanding Institutional Arrangement for Acquiring Water for Environmental Purposes: Transaction Evidence from the Western United States." *International Journal of Water Resources Development.* (March 2003): 21-28.

Lund, Jay R., and Morris S. Israel. "Water Transfers in Water Resource Systems." *Journal of Water Resources Planning.* 121.2(1995): 193-205.

Lund, J. R., Israel, M., and Kanazawa, R. *Recent California Water Transfers: Emerging Options in Water Management*, Center for Environmental and Water Resources Engineering. 1992. University of California, Davis.

Maas, A. and R Anderson. *And the Deserts Shall Rejoice: Conflict, Growth and Justice in Arid Environments.* MIT Press: Cambridge, Massachusetts, 1978.

Martin, Philip. "Impact on Farmworkers of Proposed Water Transfer from Imperial County: A Memorandom to the Latino Lagislative Caucus of the California State Senate, 2003." www.ucop.edu/cprc/farmwkr**water**transfer.pdf

Meko, David, Charles W. Stockton, and W.R. Boggess. "The Tree-Ring Record of Severe Sustained Drought." *Water Resources Bulletin.* (Oct. 1995): 789-801.

Metropolitan Water District of Southern California. "Metropolitan Calls on Water Transfer Options from Sacramento Valley Rice Farmers." (2003). http://www.mwdh2o.com/mwdh2o/pages/news/press_releases/2003-02/Options_Exercised.htm.

Michelsen, A. R. and Young, R. A. Optioning Agricultural Water Rights for Urban Water Supplies During Drought. *American Journal of Agricultural Economics.* 75(November 1993):1010-20.

Naeser, Robert Benjamin and Lynne Lewis Bennett. "The Cost of Noncompliance: The Economic Value of Water in the Middle Arkansas River Valley." *Natural Resources Journal.* 38(1998): 445-463.

National Atlas of the United States. Nationalatlas.gov. http://www-atlas.usgs.gov/natlas/Natlasstart.asp

National Oceanic and Atmospheric Administration (NOAA). "Economic Impacts of Drought and Benefits of NOAA's Drought Forecasting Services." *NOAA Magazine.* (Sept. 2002). http://www.magazine.noaa.gov/stories/mag51.htm.

National Research Council. *Water Transfers in the West*. National Academy Press: Washington D.C., 1992.

Nolte, Kurt. Yuma County Agricultural Extension. Email communication. Dec 20, 2005.

Nolte, Kurt. Yuma County Agricultural Extension. Telephone interview. April 17, 2006.

Oad, R. and P. King, "Irrigation Forbearance Feasibility Study in the Middle Rio Grande Conservancy District", MBK Consulting, LLC, July 2005.

Osborn, Dennis. Fertizona, Casa Grande, Arizona. Email communication. Sept. 9, 2005.

Osborn, Dennis. Fertizona, Casa Grande, Arizona. Email communication. Feb. 3, 2006.

Osborn, Dennis. Fertizona, Casa Grande, Arizona. Email communication. April 19, 2006.

Parker Oil, La Paz, Arizona. Telephone interview. Jan. 2006.

Pittenger, Katie, MS thesis, **"Economic Arrangements to Improve Dry-Year Supply Reliability in the Lower Colorado River Basin"**, University of Arizona, 2006.

Pontius, Dale. "The Colorado River Basin Study." Report to the Western Water Policy Review Advisory Commission. August 1997.

Reinerston, Jim. County Executive Director, Arizona Farm Service Agency, Yuma/La Paz County office. Telephone interview. May 1, 2005.

Saliba, B.C. and D. Bush, "Water Markets in Theory and Practice", Westview Press, 1987.

Southern Nevada Water Authority. "Arizona Water Bank." 2006. http://www.snwa.com/html/wr_colrvr_azbank.html.

Tadayon, Saeid. "Water withdrawals for irrigation, municipal, mining, thermoelectric-power, and drainage uses in Arizona outside of active management areas, 1991-2000." USGS Scientific Investigations Report Number 2004-5293. 2005.

Teegerstrom, Trent and Timothy Knowles. "Arizon Field Crop Budgets 1999-2000: La Paz County." March 1999. Cooperative Extension, University of Arizona. http://ag.arizona.edu/arec/ext/budgets/LaPaz-map.html.

Teegerstrom, Trent and Barry Tickes. "Arizon Field Crop Budgets 1999-2000: Yuma County." March 1999. Cooperative Extension, University of Arizona. http://ag.arizona.edu/arec/ext/budgets/Yuma-map.html.

Teegerstrom, Trent, John Palumbo, and Mohammed Zerkoune. "2000-2001 Arizona Vegetable Crop Budgets: Western Arizona." 2001. Cooperative Extension, University of Arizona. http://ag.arizona.edu/arec/ext/budgets/western.html.

Teegerstrom, Trent. University of Arizona Research Specialist. Personal interview. May 8, 2006.

Thobani, Mateen. "Meeting Water Needs in Developing Countries: Resolving Issues in Establishing Tradable Water Rights." In *Markets for Water: Potential and Performance*. Easter, K. William, Mark Rosengrant, and Ariel Dinar. Kluwer Academic Press, 1998.

Tronstad, Russell. University of Arizona Extension Economist. Personal interview. May 1, 2006.

Tronstad, Russell. University of Arizona Extension Economist. Personal interview. May 11, 2006.

Union Oil, Yuma, Arizona. Telephone interview. Jan. 2006.

USDA. "Crop Policies." 2005. http://www.rma.usda.gov/policies/.

USDA. "ERS County Typology Codes." 2004. http://www.ers.usda.gov/Data/TypologyCodes/.

USDA. "LDP Summary." 2006. http://www.fsa.usda.gov/FSA/webapp?area=home&subject=prsu&topic=psr

USDA. "Premium Subsidy Schedule." 2006. http://www2.rma.usda.gov/data/premium.html.

Water Strategist, published by Strat Econ, Claremont, California, 1994.

Weinberg, Marca. "Assessing a Policy Grab Bag: Federal Water Policy Reform." *American Journal of Agricultural Economics.* 84.3(Aug 2002): 541-556.

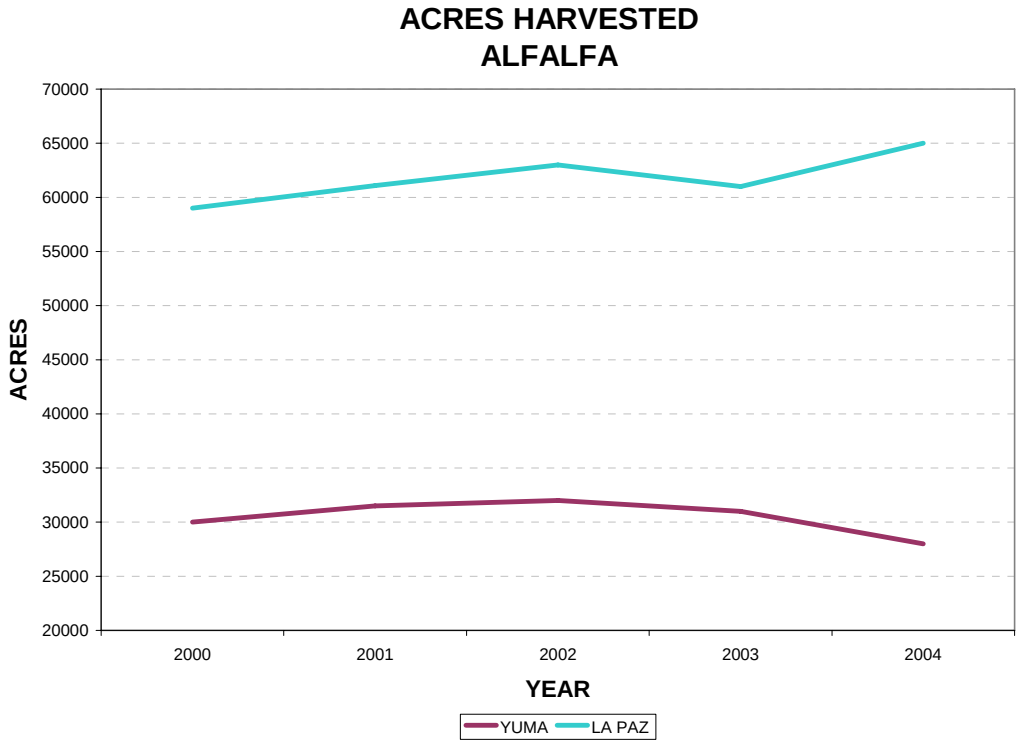
Western Regional Climate Center. "Explanation of Terms." http://www.wrcc.dri.edu/spi/explanation.html.

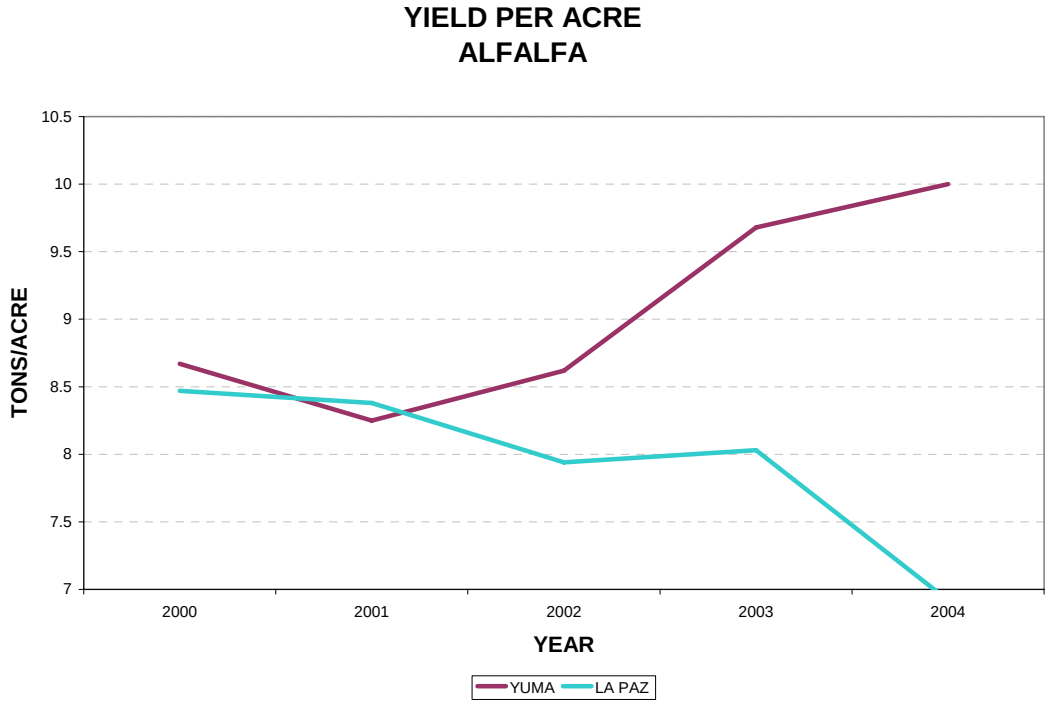
Young, Robert A. *Determining the Economic Value of Water.* Washington, D.C.: Resources for the Future, 2005.

Yuma Desalting Plant/Cienega de Santa Clara Workgroup. 2005. "Balancing Water Needs on the Lower Colorado River: Recommendations of the Yuma Desalting Plant/Cienega de Santa Clara Workgroup." http://ag.arizona.edu/AZWATER/publications/YDP%20report%20042205.pdf.

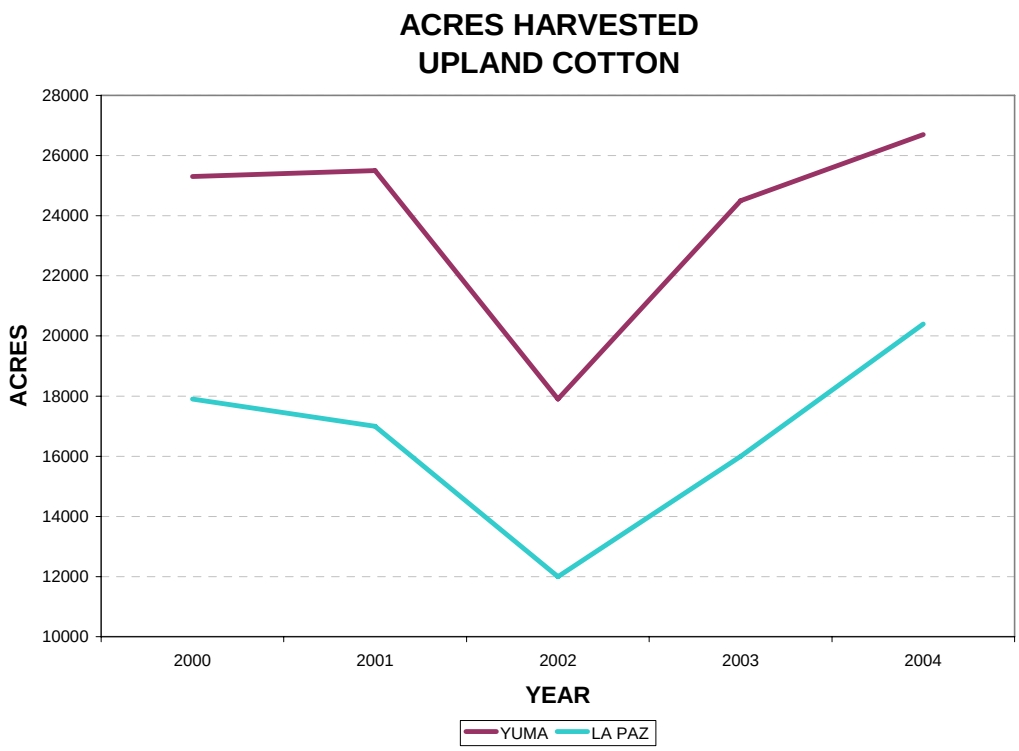
## APPENDIX ONE: Market Price and Yield Graphs

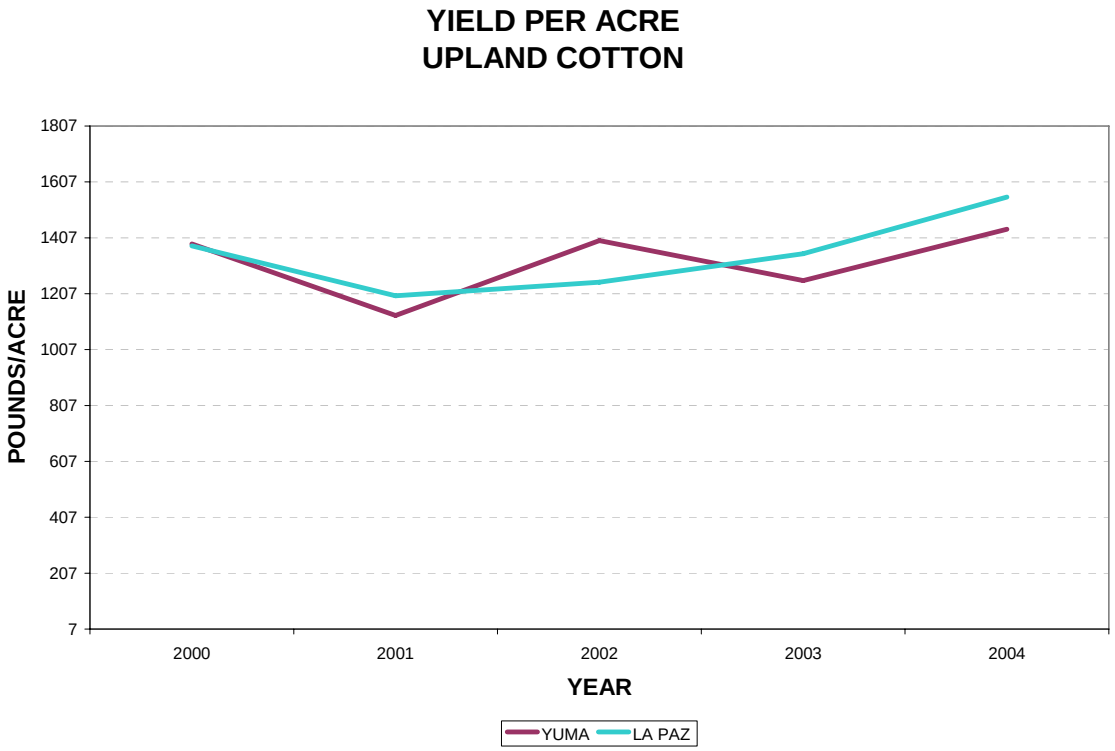
## Alfalfa 5-Year Trends

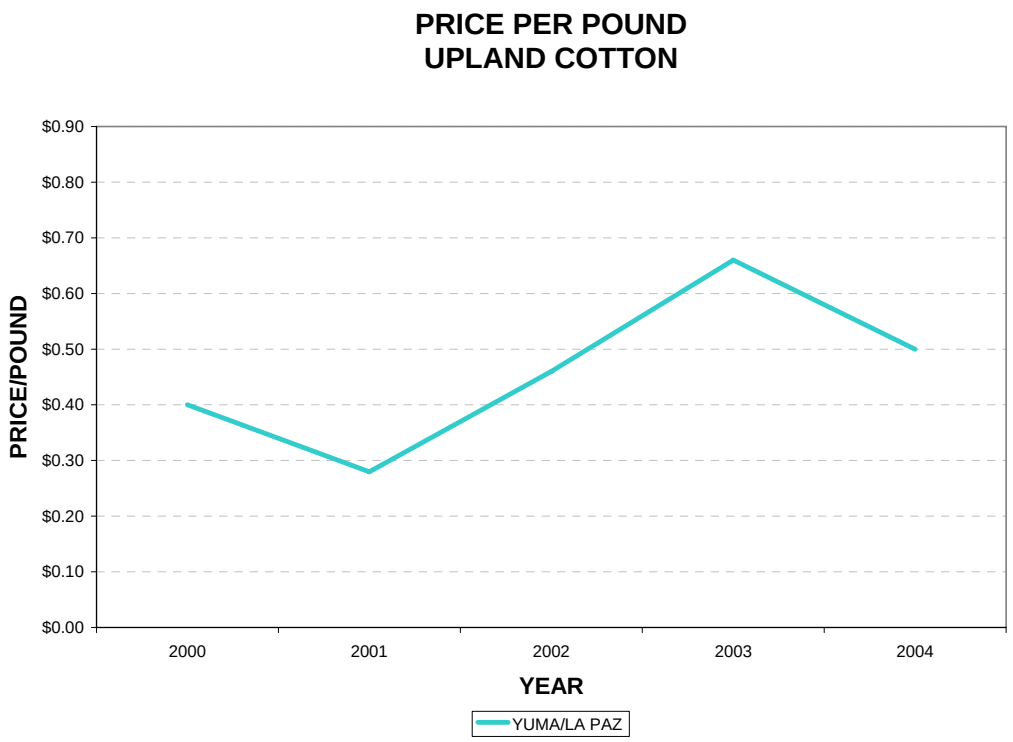


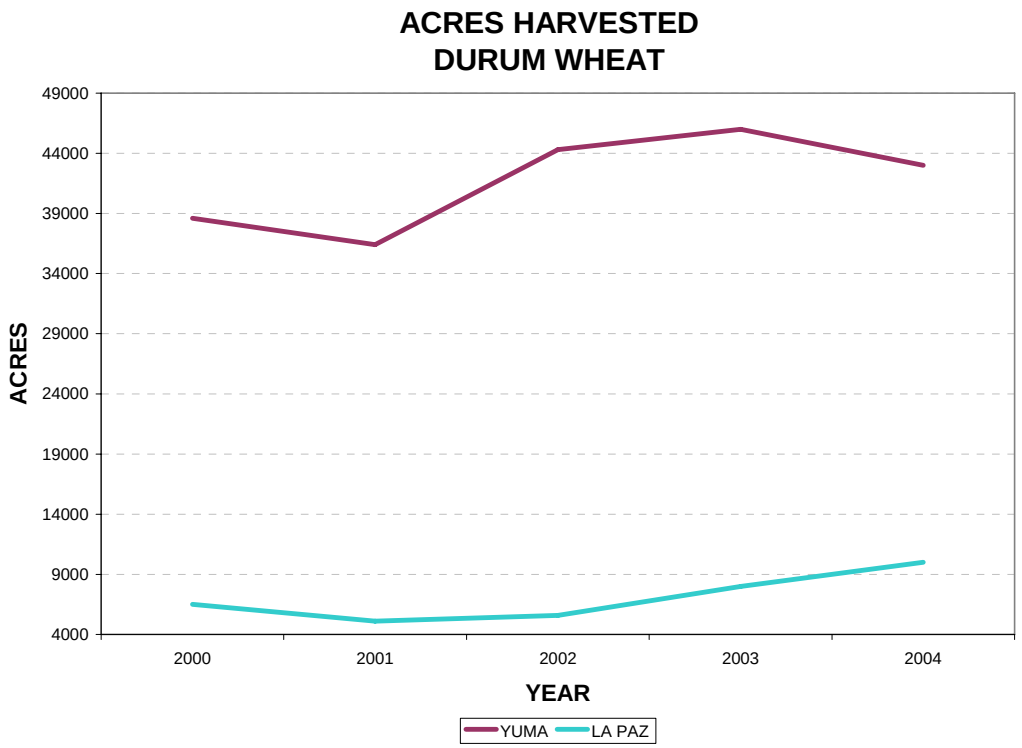
## Upland Cotton 5-Year Trends

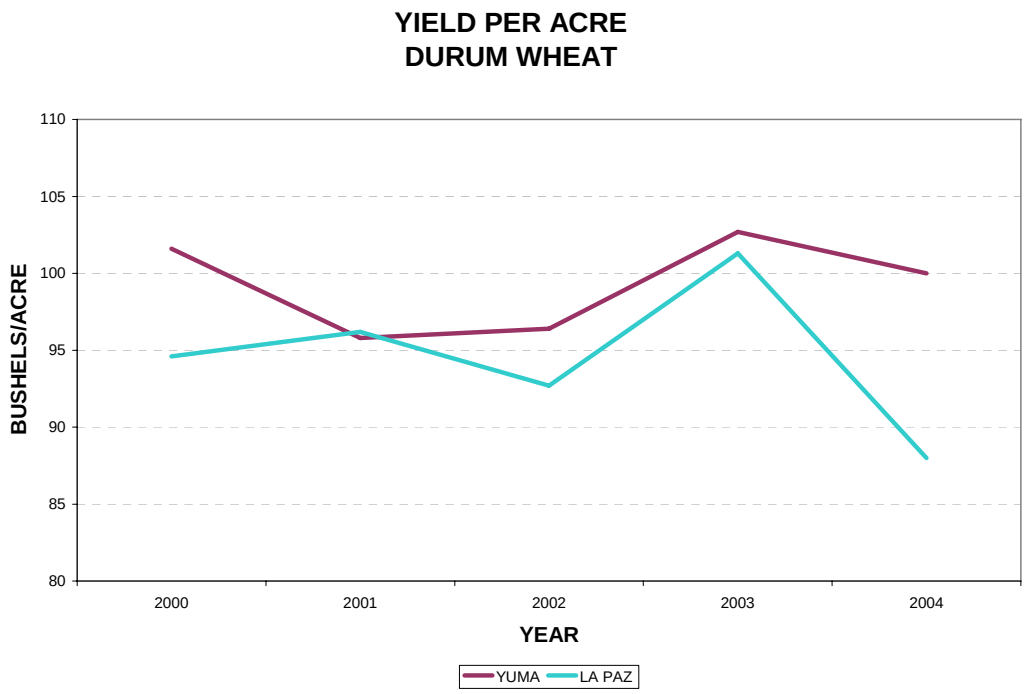


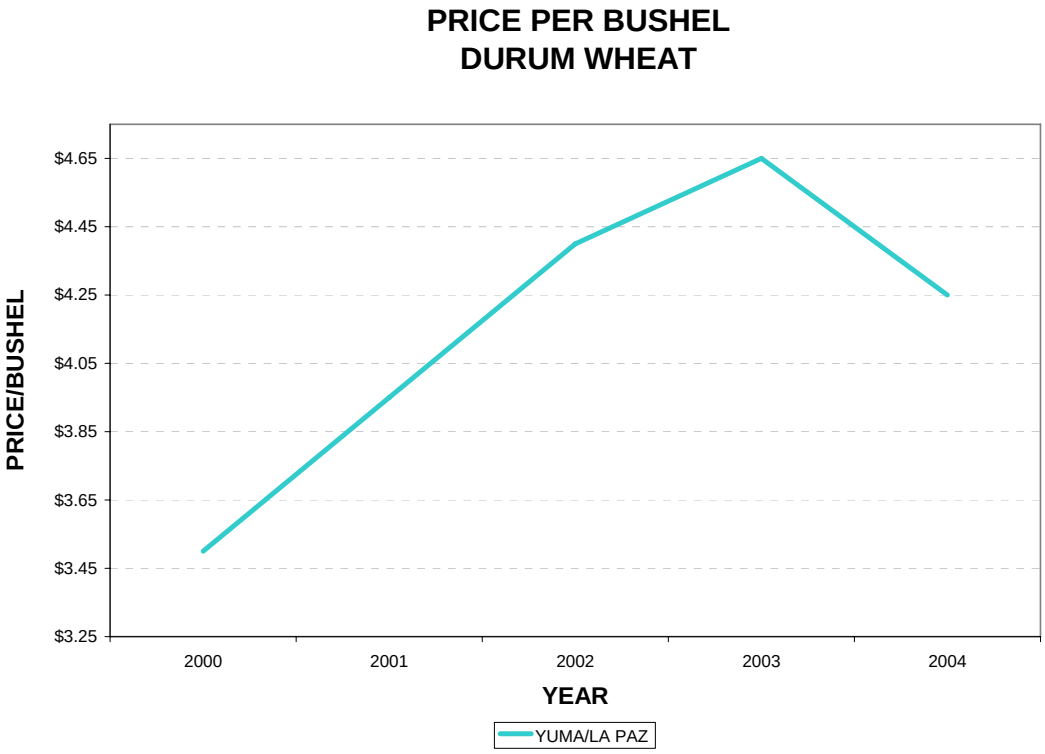


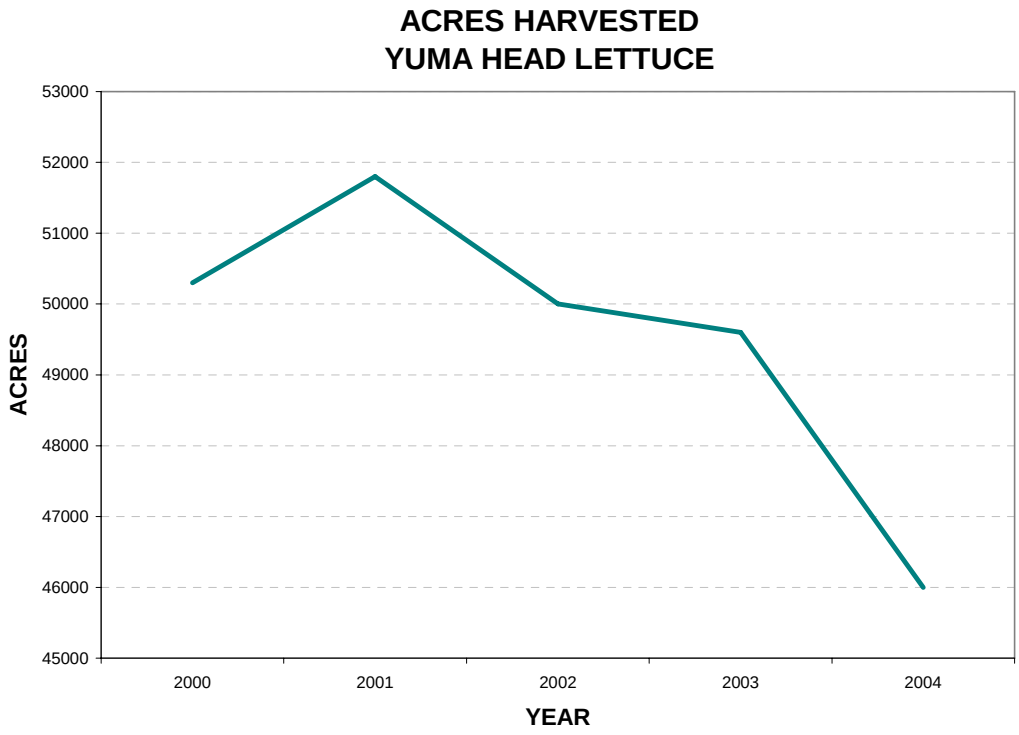

## Durum Wheat 5-Year Trends


ACRES HARVESTED
DURUM WHEAT
ACRES
49000
44000
39000
34000
29000
24000
19000
14000
9000
4000
2000
2001
2002
2003
2004
YEAR
YUMA
LA PAZ

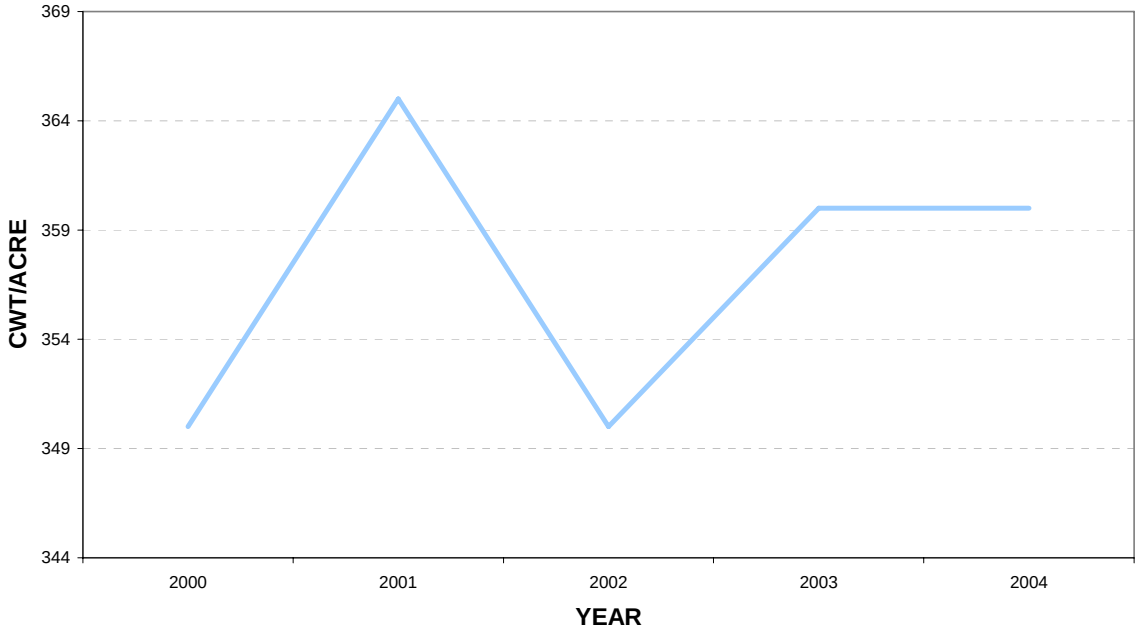

YIELD PER ACRE
DURUM WHEAT
BUSHELS/ACRE
110
105
100
95
90
85
80
2000
2001
2002
2003
2004
YEAR
YUMA
LA PAZ



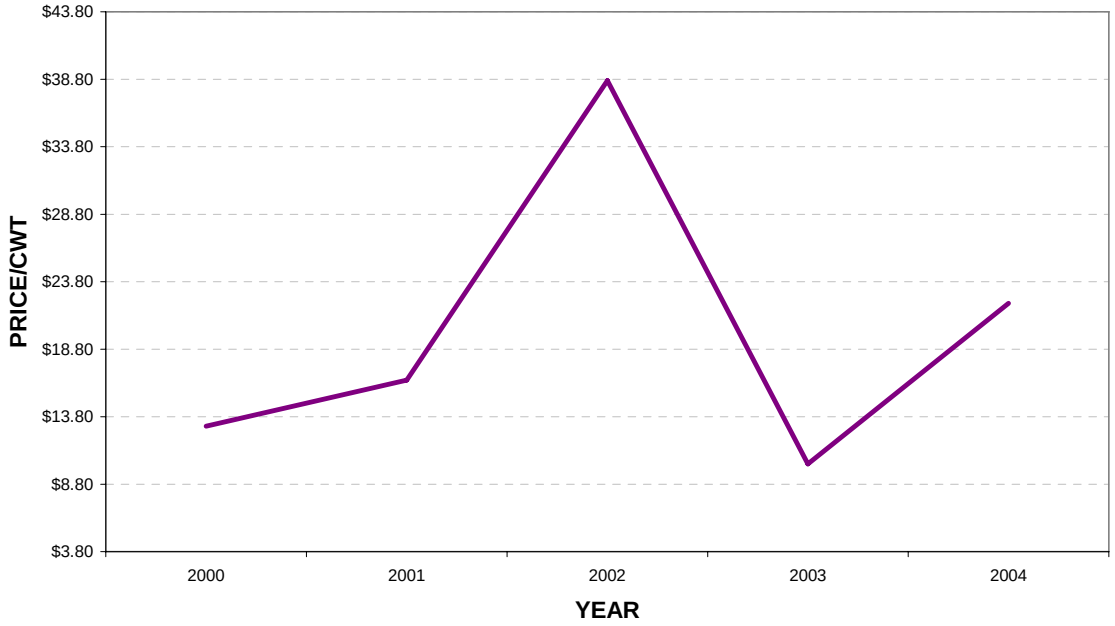

## Head Lettuce 5-Year Trends



## YIELD PER ACRE
## YUMA HEAD LETTUCE




## PRICE PER CWT
## YUMA HEAD LETTUCE



**APPENDIX TWO: Variable Costs By County and Crop**

| TOTAL VARIABLE COSTS PER ACRE (LESS WATER) | | | | |
|---|---|---|---|---|
| **YUMA COUNTY** | **Alfalfa** | **Upland Cotton** | **Durum Wheat** | **Head Lettuce** |
| **Variable Costs per Acre** | | | | |
| **Cash Land Preparation and Growing Expenses** | | | | |
| Paid Labor: | | | | |
| Tractor | 7.06 | 42.31 | 19.08 | 35.95 |
| Hand | 0 | 24.27 | 0 | 0 |
| Irrigation | 40.71 | 9.51 | 20.46 | 42.09 |
| Other/Contract | 0 | 0 | 0 | 1.87 |
| Chemicals and Custom Applications | | | | |
| Fertilizer | 15.37 | 93.5 | 138.55 | 221.42 |
| Insecticide | 23.78 | 299.66 | 17.34 | 251.65 |
| Herbicide | 27.16 | 5.74 | 43.86 | 124.02 |
| Other Chemicals | 0 | 0 | 0 | 52.85 |
| Farm Machinery/Vehicles: | | | | |
| Diesel Fuel | 9.57 | 48.31 | 26.42 | 52.22 |
| Gasoline | 0 | 10.43 | 0 | 2.05 |
| Repairs and Maintenance | 4.2 | 27.8 | 12.83 | 28.87 |
| Other Purchased Inputs | | | | |
| Seeds/Transplants | 14.31 | 0.13 | 26.5 | 114.48 |
| Other Services and Rentals | 0 | 245.88 | 42.88 | 239.1 |
| **Total Land Prep and Growing Expenses** | 142.16 | 807.54 | 347.92 | 1166.57 |
| **Cash Harvest and Post Harvest Expenses** | | | | |
| Paid Labor: | | | | |
| Tractor | 25.29 | 5.99 | 0 | 0 |
| Other/Contract | 31.15 | 7.98 | 0 | 0 |
| Chemicals and Custom Applications | | | | |
| Insecticide | 0 | 27.26 | 0 | 0 |
| Other Chemicals | 0 | 42.04 | 0 | 0 |
| Farm Machinery/Vehicles: | | | | |
| Diesel Fuel | 68.56 | 21.02 | 0 | 0 |
| Repairs and Maintenance | 137.05 | 50.38 | 0 | 0 |
| Other Materials | 55.97 | 0 | 0 | 0 |
| Custom Harvest/Post Harvest | 0 | 53.43 | 73.43 | 2167.2 |
| Cotton Ginning | 0 | 112.67 | 0 | 0 |

| | | | | |
|---|---|---|---|---|
| Crop Assessment | 0 | 9.38 | 0 | 0 |
| Other Materials | 0 | 1.6 | 0 | 0 |
| **Total Harvest and Post Harvest Expenses** | 318.02 | 331.75 | 73.43 | 2167.2 |
| Operating Overhead | | | | |
| Pickup use | 21.04 | 25.24 | 12.62 | 21.04 |
| Operating Interest | 25.59 | 29.84 | 7.9 | 18.75 |
| **TOTAL VARIABLE COSTS PER ACRE** | 506.81 | 1194.37 | 441.87 | 3373.56 |

## TOTAL VARIABLE COSTS PER ACRE (LESS WATER)

| LA PAZ COUNTY | Alfalfa (w/ sheep) | Upland Cotton | Durum Wheat |
|---|---|---|---|
| **Variable Costs per Acre** | | | |
| **Cash Land Preparation and Growing Expenses** | | | |
| Paid Labor: | | | |
| Tractor | 2.23 | 33.45 | 11.19 |
| Hand | 0 | 30.68 | 0 |
| Irrigation | 40.84 | 24.26 | 37.06 |
| Other/Contract | 0 | 0 | 0 |
| Chemicals and Custom Applications | | | |
| Fertilizer | 28.64 | 102.63 | 58.21 |
| Insecticide | 45.91 | 187.67 | 8.44 |
| Herbicide | 13.59 | 29.25 | 20.68 |
| Other Chemicals | 0 | 110.57 | 0 |
| Farm Machinery/Vehicles: | | | |
| Diesel Fuel | 2.91 | 77.27 | 20.64 |
| Gasoline | 0 | 32.03 | 0 |
| Repairs and Maintenance | 1.11 | 0 | 8.31 |
| Other Purchased Inputs | | | |
| Seeds/Transplants | 10.73 | 0.13 | 34.45 |
| Other Services and Rentals | 0 | 55.38 | 0 |
| **Total Land Prep and Growing Expenses** | 145.96 | 683.32 | 198.98 |
| **Cash Harvest and Post Harvest Expenses** | | | |
| Paid Labor: | | | |
| Tractor | 14.04 | 6.55 | 1.95 |
| Other/Contract | 26.63 | 12.78 | 0 |
| Chemicals and Custom Applications | | | |
| Insecticide | 0 | 0 | 0 |

| | | | |
|---|---|---|---|
| Other Chemicals | 0 | 59.45 | 0 |
| Farm Machinery/Vehicles: | | | |
| Diesel Fuel | 43.42 | 36.49 | 3.02 |
| Repairs and Maintenance | 90.59 | 82.91 | 1.64 |
| Other Materials | 27.3 | 0 | 0 |
| Custom Harvest/Post Harvest | 0 | 3.36 | 67.58 |
| Cotton Ginning | 0 | 108.87 | 0 |
| Crop Assessment | 0 | 9.56 | 0 |
| Other Materials | 0 | 1.59 | 0 |
| **Total Harvest and Post Harvest Expenses** | 201.98 | 321.56 | 74.19 |
| Operating Overhead | | | |
| Pickup use | 16.92 | 25.38 | 12.69 |
| Operating Interest | 21.23 | 30.52 | 7.03 |
| **TOTAL VARIABLE COSTS PER ACRE** | 386.09 | 1060.78 | 292.89 |

## APPENDIX THREE: NROVC Calculations

| Yuma Alfalfa Production | 2004 | 5yr Avg | High | Low |
|---|---|---|---|---|
| **Revenue per Acre** | | | | |
| Yield/acre | 10 | 9.044 | 10 | 8.25 |
| Price/unit | 99.5 | 96.4 | 100 | 89.5 |
| LDP Rate | 0 | 0 | 0 | 0 |
| Price Plus LDP per unit | 99.5 | 96.4 | 100 | 89.5 |
| Gross Revenue ($/Acre) | 995 | 871.8416 | 1000 | 738.375 |
| **Total Variable Costs per Acre** | 506.81 | 506.81 | 506.81 | 506.81 |
| **Net Returns Over Variable Costs Per Acre** | 488.19 | 365.0316 | 493.19 | 231.565 |
| A/F of water applied per acre | 5.8 | 5.8 | 5.8 | 5.8 |
| **Net Returns Over Variable Costs Per Acre-foot of water applied** | 84.17 | 62.94 | 85.03 | 39.93 |

| Yuma Upland Cotton | 2004 | 5yr Avg | High | Low |
|---|---|---|---|---|
| **Revenue per Acre** | | | | |
| Yield/acre (lint) | 1438 | 1320.6 | 1438 | 1129 |
| Price/unit (lint) | 0.5 | 0.4616 | 0.664 | 0.284 |
| Yield/acre (seed) | 1.24 | 1.06 | 1.24 | 0.87 |
| Price/unit (seed) | 160 | 139.2 | 160 | 124 |
| LDP/Marketing Gain Rate | 0.149 | 0.143 | 0.076 | 0.28 |
| Price Plus LDP per unit | 0.649 | 0.6046 | 0.74 | 0.564 |
| Gross Revenue ($/Acre) | 1131.662 | 945.98676 | 1262.52 | 744.636 |
| **Total Variable Costs per Acre** | 1194.37 | 1194.37 | 1194.37 | 1194.37 |
| **Net Returns Over Variable Costs Per Acre** | -62.708 | -248.38324 | 68.15 | -449.734 |
| A/F of water applied per acre | 4.2 | 4.2 | 4.2 | 4.2 |
| **Net Returns Over Variable Costs Per Acre-foot of water applied** | -14.93 | -59.14 | 16.23 | -107.08 |

| Yuma Durum Wheat | 2004 | 5yr Avg | High | Low |
|---|---|---|---|---|
| **Revenue per Acre** | | | | |
| Yield/acre | 100 | 99.3 | 102.7 | 95.8 |
| Price/bushel | 4.25 | 4.15 | 4.65 | 3.5 |
| LDP Rate | 0 | 0 | 0 | 0 |
| Price Plus LDP per unit | 4.25 | 4.15 | 4.65 | 3.5 |
| Gross Revenue ($/Acre) | 425 | 412.095 | 477.555 | 335.3 |
| **Total Variable Costs per Acre** | 441.87 | 441.87 | 441.87 | 441.87 |
| **Net Returns Over Variable Costs Per Acre** | -16.87 | -29.775 | 35.685 | -106.57 |
| A/F of water applied per acre | 3.5 | 3.5 | 3.5 | 3.5 |
| **Net Returns Over Variable Costs Per Acre-foot of water applied** | -4.82 | -8.51 | 10.20 | -30.45 |

| Yuma Head Lettuce | 2004 | 5yr Avg | High | Low |
|---|---|---|---|---|
| **Revenues per Acre** | | | | |
| Yield/acre | 360 | 357 | 365 | 350 |
| Price/cwt | 22.2 | 20.16 | 38.7 | 10.3 |
| LDP Rate | 0 | 0 | 0 | 0 |
| Price Plus LDP per unit | 22.2 | 20.16 | 38.7 | 10.3 |
| Gross Revenue ($/Acre) | 7992 | 7197.12 | 14125.5 | 3605 |
| **Total Variable Costs per Acre** | 3373.56 | 3373.56 | 3373.56 | 3373.56 |
| **Net Returns Over Variable Costs Per Acre** | 4618.44 | 3823.56 | 10751.94 | 231.44 |
| A/F water applied per acre | 3.6 | 3.6 | 3.6 | 3.6 |
| **Net Returns Over Variable Costs Per Acre-foot of Water Applied** | 1282.90 | 1062.10 | 2986.65 | 64.29 |

| LA PAZ Alfalfa Production | 2004 | 5yr Avg | High | Low |
|---|---|---|---|---|
| **Revenues per Acre** | | | | |
| Yield/acre | 6.92 | 7.948 | 8.47 | 6.92 |
| Price/unit | 99.5 | 96.4 | 100 | 89.5 |
| Sheep Grazing Head Days | 200 | 200 | 200 | 200 |
| Price/unit | 0.09 | 0.09 | 0.09 | 0.09 |
| LDP Rate | 0 | 0 | 0 | 0 |
| Price Plus LDP per unit | 99.5 | 96.4 | 100 | 89.5 |
| Gross Revenue ($/Acre) | 706.54 | 784.1872 | 865 | 637.34 |
| **Total Variable Costs per Acre** | 386.09 | 386.09 | 386.09 | 386.09 |
| **Net Returns Over Variable Costs Per Acre** | 320.45 | 398.0972 | 478.91 | 251.25 |
| A/F water applied per acre | 5.8 | 5.8 | 5.8 | 5.8 |
| **Net Returns Over Variable Costs Per Acre-foot of Water Applied** | 55.25 | 68.64 | 82.57 | 43.32 |

| LA PAZ Upland Cotton | 2004 | 5yr Avg | High | Low |
|---|---|---|---|---|
| **Revenues per Acre** | | | | |
| Yield/acre | 1553 | 1345.8 | 1553 | 1200 |
| Price/unit | 0.444 | 0.45 | 0.664 | 0.284 |
| Yield/acre (seed) | 1.34 | 1.08 | 1.34 | 0.93 |
| Price/unit (seed) | 163 | 139.8 | 163 | 124 |
| LDP Rate | 0.149 | 0.143 | 0.076 | 0.28 |
| Price Plus LDP per unit | 0.593 | 0.593 | 0.74 | 0.564 |
| Gross Revenue ($/Acre) | 1139.349 | 949.0434 | 1367.64 | 792.12 |
| **Total Variable Costs per Acre** | 1060.78 | 1060.78 | 1060.78 | 1060.78 |
| **Net Returns Over Variable Costs Per Acre** | 78.569 | -111.7366 | 306.86 | -268.66 |
| A/F water applied per acre | 4.2 | 4.2 | 4.2 | 4.2 |
| **Net Returns Over Variable Costs Per Acre-foot of Water Applied** | 18.71 | -26.60 | 73.06 | -63.97 |

| LA PAZ Durum Wheat | 2004 | 5yr Avg | High | Low |
|---|---|---|---|---|
| **Revenues per Acre** | | | | |
| Yield/acre | 88 | 94.56 | 101.3 | 88 |
| Price/unit | 4.25 | 4.15 | 4.65 | 3.5 |
| LDP Rate | 0 | 0 | 0 | 0 |
| Price Plus LDP per unit | 4.25 | 4.15 | 4.65 | 3.5 |
| Gross Revenue ($/Acre) | 374 | 392.424 | 471.045 | 308 |
| **Total Variable Costs per Acre** | 292.89 | 292.89 | 292.89 | 292.89 |
| **Net Returns Over Variable Costs Per Acre** | 81.11 | 99.534 | 178.155 | 15.11 |
| A/F water applied per acre | 3.5 | 3.5 | 3.5 | 3.5 |
| **Net Returns Over Variable Costs Per Acre-foot of Water Applied** | 23.17 | 28.44 | 50.90 | 4.32 |

2005 & 2004 Arizona Agricultural Statistics Bulletins, yield and price data.
County cottonseed yield/acre computed using actual statewide cotton lint/seed ratio 2000-2004, 2005 & 2004 Arizona Agricultural Statistics Bulletins.
USDA "LDP Summary," LDP and marketing gain rate data.
2002 Census of Agriculture, water application rates

## APPENDIX FOUR: SEASONAL OPERATIONS AND CUMULATIVE COSTS

**County:** Yuma
**Crop:** Hay Alfalfa
**Tot. Variable Cost:** $541.11

| Month | Operations | Class | Cost | Running Total ($) | % of Total Variable Cost | Running Total (%) |
|---|---|---|---|---|---|---|
| Jan | Irrigate | Growing | 58.98 | 58.98 | 10.90 | 10.90 |
| Jan | Swathing | Harvest | 66.87 | 125.85 | 12.36 | 23.26 |
| Jan | Raking | Harvest | 27.90 | 153.75 | 5.16 | 28.41 |
| Jan | Bailing | Harvest | 141.48 | 295.23 | 26.15 | 54.56 |
| Jan | Roadsiding | Harvest | 81.76 | 376.99 | 15.11 | 69.67 |
| Feb | Rerun Borders | Growing | 10.68 | 387.67 | 1.97 | 71.64 |
| Feb | Apply Herbicide/Ground | Growing | 32.26 | 419.93 | 5.96 | 77.61 |
| Mar | Apply Insecticide/Air | Growing | 32.26 | 452.19 | 5.96 | 83.57 |
| Sep | Irrigate/Run Fertilizer | Growing | 22.93 | 475.12 | 4.24 | 87.80 |
| Oct | Renovate | Growing | 1.72 | 476.84 | 0.32 | 88.12 |
| Oct | Plant | Land Prep | 17.64 | 494.48 | 3.26 | 91.38 |
| Misc. | Pickup Use | | 21.04 | 515.52 | 3.89 | 95.27 |
| | Operating Interest | | 25.59 | 541.11 | 4.73 | 100.00 |
| | | | | | | |
| TOTAL | | | 541.11 | 541.11 | 100.00 | 100.00 |

**County:** La Paz
**Crop:** Hay Alfalfa (w/ Grazing)
**Tot. Variable Cost:** $438.44

| Month | Operations | Class | Cost | Running Total ($) | % of Total Variable Cost | Running Total (%) |
|---|---|---|---|---|---|---|
| Jan | Irrigate | Growing | 40.76 | 40.76 | 9.30 | 9.30 |
| Mar | Swathing | Harvest | 12.27 | 53.03 | 2.80 | 12.10 |
| Mar | Raking | Harvest | 42.06 | 95.09 | 9.59 | 21.69 |
| Mar | Bailing | Harvest | 78.79 | 173.88 | 17.97 | 39.66 |
| Mar | Roadsiding | Harvest | 68.85 | 242.73 | 15.70 | 55.36 |
| Mar | Irrigate/Run Fertilizer | Growing | 55.64 | 298.37 | 12.69 | 68.05 |
| Apr | Apply Herbicide/Air | Growing | 13.59 | 311.96 | 3.10 | 71.15 |
| Apr | Apply Insecticide/Air | Growing | 14.42 | 326.38 | 3.29 | 74.44 |
| May | Apply Insecticide/Air | Growing | 56.93 | 383.31 | 12.98 | 87.43 |
| Oct | Scratch | Growing | 4.54 | 387.85 | 1.04 | 88.46 |
| Oct | Plant | Land Prep | 12.44 | 400.29 | 2.84 | 91.30 |
| Misc. | Pickup Use | | 16.92 | 417.21 | 3.86 | 95.16 |
| | Operating Interest | | 21.23 | 438.44 | 4.84 | 100.00 |
| | | | | | | |
| TOTAL | | | 438.44 | 438.44 | 100.00 | 100.00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **County:** | **Yuma** | | | | | |
| **Crop:** | **Upland Cotton** | | | | | |
| **Tot. Variable Cost:** | **$1,194.36** | | | | | |
| **Month** | **Operations** | **Class** | **Cost** | **Running Total ($)** | **% of Total Variable Cost** | **Running Total (%)** |
| Dec | Rip | Lnd Prep | 10.10 | 10.10 | 0.85 | 0.85 |
| Dec | Disk | Lnd Prep | 12.48 | 22.58 | 1.04 | 1.89 |
| Jan | Laser Level | Lnd Prep | 52.46 | 75.04 | 4.39 | 6.28 |
| Jan | Roll Beds | Growing | 2.38 | 77.42 | 0.20 | 6.48 |
| Jan | List | Lnd Prep | 6.97 | 84.39 | 0.58 | 7.07 |
| Feb | Preirrigate | Growing | 6.39 | 90.78 | 0.54 | 7.60 |
| Mar | Mulch | Lnd Prep | 5.52 | 96.30 | 0.46 | 8.06 |
| Mar | Plant | Lnd Prep | 8.30 | 104.60 | 0.69 | 8.76 |
| Mar | Remove Cap | Growing | 4.46 | 109.06 | 0.37 | 9.13 |
| Apr | Cultivate | Growing | 20.70 | 129.76 | 1.73 | 10.86 |
| Apr | Soil Fertility | Growing | 3.00 | 132.76 | 0.25 | 11.12 |
| May | Irrigate/Run Fertilizer | Growing | 56.02 | 188.78 | 4.69 | 15.81 |
| Jun | Irrigate | Growing | 6.39 | 195.17 | 0.54 | 16.34 |
| Jun | Hand Weeding | Growing | 100.00 | 295.17 | 8.37 | 24.71 |
| Jun | Apply Insectidie/Ground | Growing | 43.43 | 338.60 | 3.64 | 28.35 |
| Jun | Apply Herbicide/Ground | Growing | 10.49 | 349.09 | 0.88 | 29.23 |
| Jul | Apply Insectidie/Ground | Growing | 198.40 | 547.49 | 16.61 | 45.84 |
| Jul | Apply Insecticide/Ground | Growing | 15.57 | 563.06 | 1.30 | 47.14 |
| Jul | Hand Weeding | Growing | 100.00 | 663.06 | 8.37 | 55.52 |
| Jul | Apply Insecticide/Air | Growing | 14.89 | 677.95 | 1.25 | 56.76 |
| Aug | Apply Insecticide/Air | Growing | 10.95 | 688.90 | 0.92 | 57.68 |
| Aug | Apply Insecticide/Air | Growing | 16.17 | 705.07 | 1.35 | 59.03 |
| Aug | Irrigate/Run Fertilizer | Growing | 48.97 | 754.04 | 4.10 | 63.13 |
| Sep | Apply Insecticide/Air | Growing | 15.70 | 769.74 | 1.31 | 64.45 |
| Sep | Apply Defoliant/Air | Harvest | 43.59 | 813.33 | 3.65 | 68.10 |
| Sep | Apply Defoliant/Air | Harvest | 25.71 | 839.04 | 2.15 | 70.25 |
| Sep | Dust Control | Growing | 24.97 | 864.01 | 2.09 | 72.34 |
| Sep | Prepare Ends | Harvest | 1.22 | 865.23 | 0.10 | 72.44 |
| Sep | Cotton, First Pick | Harvest | 67.46 | 932.69 | 5.65 | 78.09 |
| Sep | Cotton, Make Mounds | Harvest | 13.60 | 946.29 | 1.14 | 79.23 |
| Sep | Cotton, Rood | Harvest | 43.33 | 989.62 | 3.63 | 82.86 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Sep | Haul | Harvest | 6.80 | 996.42 | 0.57 | 83.43 |
| Sep | Cotton Ginning | Post Hvst | 112.67 | 1109.09 | 9.43 | 92.86 |
| Dec | Cotton Classing | Marketing | 3.30 | 1112.39 | 0.28 | 93.14 |
| Dec | Crop Assessment | Marketing | 9.38 | 1121.77 | 0.79 | 93.92 |
| Dec | Cut Stalks | Post Hvst | 4.69 | 1126.46 | 0.39 | 94.31 |
| Dec | Disk Residue | Lnd Prep | 12.82 | 1139.28 | 1.07 | 95.39 |
| Misc. | Pickup Use | | 25.24 | 1164.52 | 2.11 | 97.50 |
| | Operating Inerest 6% | | 29.84 | 1194.36 | 2.50 | 100.00 |
| | | | | | | |
| | TOTAL | | 1194.36 | 1194.36 | 100.00 | 100.00 |

| | |
|---|---|
| **County:** | **La Paz** |
| **Crop:** | **Upland Cotton** |
| **Tot. Variable Cost:** | **$1,151.62** |

| **Month** | **Operations** | **Class** | **Cost** | **Running Total ($)** | **% of Total Var. Cost** | **Running Total (%)** |
|---|---|---|---|---|---|---|
| Dec | Disk | Lnd Prep | 13.03 | 13.03 | 1.13 | 1.13 |
| Dec | Rip | Lnd Prep | 38.84 | 51.87 | 3.37 | 4.50 |
| Dec | Laser Level | Lnd Prep | 42.88 | 94.75 | 3.72 | 8.23 |
| Jan | Soil Fertility | Growing | 12.00 | 106.75 | 1.04 | 9.27 |
| Jan | Apply Herbicide/Ground | Growing | 19.11 | 125.86 | 1.66 | 10.93 |
| Jan | Apply Fertilizer/Ground | Growing | 18.66 | 144.52 | 1.62 | 12.55 |
| Feb | List | Lnd Prep | 6.49 | 151.01 | 0.56 | 13.11 |
| Feb | Buck Rows | Growing | 3.32 | 154.33 | 0.29 | 13.40 |
| Feb | Preirrigate | Growing | 3.83 | 158.16 | 0.33 | 13.73 |
| Feb | Disk Ends | Growing | 1.88 | 160.04 | 0.16 | 13.90 |
| Feb | Mulch | Lnd Prep | 6.87 | 166.91 | 0.60 | 14.49 |
| Mar | Plant | Growing | 7.11 | 174.02 | 0.62 | 15.11 |
| Apr | Remove Cap | Growing | 3.31 | 177.33 | 0.29 | 15.40 |
| Apr | Cultivate | Growing | 15.62 | 192.95 | 1.36 | 16.75 |
| Apr | Apply Fertilizer/Inject | Growing | 92.28 | 285.23 | 8.01 | 24.77 |
| Apr | Apply Herbicide/Ground | Growing | 22.94 | 308.17 | 1.99 | 26.76 |
| May | Irrigate | Growing | 17.88 | 326.05 | 1.55 | 28.31 |
| Jun | Irrigate/Run Fertilizer | Growing | 18.67 | 344.72 | 1.62 | 29.93 |
| Jun | Field Scouting | Growing | 6.50 | 351.22 | 0.56 | 30.50 |
| Jun | Apply Growth Regulator | Growing | 47.12 | 398.34 | 4.09 | 34.59 |
| Jun | Apply Insecticide/Air | Growing | 144.38 | 542.72 | 12.54 | 47.13 |
| Jul | Hand Weeding | Growing | 30.68 | 573.40 | 2.66 | 49.79 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Jul | Apply Insecticide/Air | Growing | 22.68 | 596.08 | 1.97 | 51.76 |
| Jul | Apply Insecticide/Air | Growing | 22.83 | 618.91 | 1.98 | 53.74 |
| Jul | Apply Insecticide/Air | Growing | 25.38 | 644.29 | 2.20 | 55.95 |
| Jul | Apply Insecticide/Air | Growing | 25.81 | 670.10 | 2.24 | 58.19 |
| Aug | Apply Insecticide/Air | Growing | 32.11 | 702.21 | 2.79 | 60.98 |
| Aug | Apply Insecticide/Air | Growing | 20.86 | 723.07 | 1.81 | 62.79 |
| Aug | Apply Insecticide/Air | Growing | 20.61 | 743.68 | 1.79 | 64.58 |
| Sep | Apply Growth Regulator | Growing | 21.29 | 764.97 | 1.85 | 66.43 |
| Sep | Apply Defoliant/Air | Harvest | 30.71 | 795.68 | 2.67 | 69.09 |
| Sep | Apply Defoliant/Air | Harvest | 28.73 | 824.41 | 2.49 | 71.59 |
| Oct | Prepare Ends | Harvest | 0.74 | 825.15 | 0.06 | 71.65 |
| Nov | Cotton, First Pick | Harvest | 79.87 | 905.02 | 6.94 | 78.59 |
| Nov | Cotton, Make Modules | Harvest | 17.72 | 922.74 | 1.54 | 80.13 |
| Nov | Haul, Custom | Harvest | 0.00 | 922.74 | 0.00 | 80.13 |
| Dec | Cotton Ginning | Post Hvst | 108.87 | 1031.61 | 9.45 | 89.58 |
| Dec | Cotton Classing | Marketing | 3.36 | 1034.97 | 0.29 | 89.87 |
| Dec | Cotton, Second Pick | Harvest | 35.05 | 1070.02 | 3.04 | 92.91 |
| Dec | Crop Assessment | Marketing | 9.56 | 1079.58 | 0.83 | 93.74 |
| Dec | Cut Stalks | Post Hvst | 6.95 | 1086.53 | 0.60 | 94.35 |
| Dec | Disk Residue | Lnd Prep | 9.19 | 1095.72 | 0.80 | 95.15 |
| Misc. | Pickup Use | | 25.38 | 1121.10 | 2.20 | 97.35 |
| | Operating Interest 6% | | 30.52 | 1151.62 | 2.65 | 100.00 |
| | TOTAL | | 1151.62 | 1151.62 | 100.00 | 100.00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **County:** | **Yuma** | | | | | |
| **Crop:** | **Durum Wheat** | | | | | |
| **Total Variable Cost:** | **$441.88** | | | | | |
| **Month** | **Operations** | **Class** | **Cost** | **Running Total ($)** | **% of Total Variable Cost** | **Running Total (%)** |
| Dec | Disk | Land Prep. | 19.87 | 19.87 | 4.50 | 4.50 |
| Dec | Roll Beds | Land Prep. | 2.38 | 22.25 | 0.54 | 5.04 |
| Dec | Laser Level | Land Prep. | 42.88 | 65.13 | 9.70 | 14.74 |
| Dec | Apply Fert/Ground | Growing | 63.34 | 128.47 | 14.33 | 29.07 |
| Dec | Plant | Land Prep. | 34.02 | 162.49 | 7.70 | 36.77 |
| Jan | Make Borders | Growing | 2.42 | 164.91 | 0.55 | 37.32 |
| Jan | Irrigate | Growing | 5.12 | 170.03 | 1.16 | 38.48 |
| Feb | Apply Herb/Ground | Growing | 27.58 | 197.61 | 6.24 | 44.72 |
| Feb | Irrigate/Run Fert | Growing | 85.72 | 283.33 | 19.40 | 64.12 |
| Feb | Apply Herb/Ground | Growing | 24.21 | 307.54 | 5.48 | 69.60 |
| Mar | Apply Insect/Air | Growing | 17.34 | 324.88 | 3.92 | 73.52 |
| Mar | Irrigate | Growing | 10.23 | 335.11 | 2.32 | 75.84 |
| Jun | Combine Harvest | Harvest | 57.68 | 392.79 | 13.05 | 88.89 |
| Jun | Haul | Harvest | 15.75 | 408.54 | 3.56 | 92.45 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Jun | Disk Residue | Land Prep. | 12.82 | 421.36 | 2.90 | 95.36 |
| Misc. | Pickup Use | | 12.62 | 433.98 | 2.86 | 98.21 |
| Misc. | Op. Interest 6% | | 7.90 | 441.88 | 1.79 | 100.00 |
| | | | | | | |
| | TOTAL | | 441.88 | 441.88 | 100.00 | 100.00 |

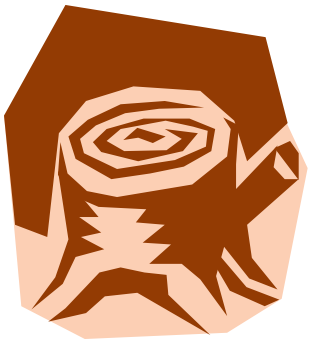
| | | | | | | |
|---|---|---|---|---|---|---|
| **County:** | **La Paz** | | | | | |
| **Crop:** | **Durum Wheat** | | | | | |
| **Tot. Variable Cost:** | **$292.70** | | | | | |
| **Month** | **Operations** | **Class** | **Cost** | **Running Total ($)** | **% of Tot Variable Cost** | **Running Total (%)** |
| Dec | Disk | Land Prep. | 9.66 | 9.66 | 3.30 | 3.30 |
| Dec | Apply Fert/Ground | Growing | 49.39 | 59.05 | 16.87 | 20.17 |
| Dec | Landplane | Land Prep. | 10.29 | 69.34 | 3.52 | 23.69 |
| Dec | Plant | Land Prep. | 41.46 | 110.80 | 14.16 | 37.85 |
| Dec | Make Borders | Growing | 2.88 | 113.68 | 0.98 | 38.84 |
| Dec | Preirrigate | Growing | 3.83 | 117.51 | 1.31 | 40.15 |
| Feb | Irrigate | Growing | 10.21 | 127.72 | 3.49 | 43.64 |
| Mar | Apply Herb/Ground | Growing | 25.27 | 152.99 | 8.63 | 52.27 |
| Mar | Irrigate/Run Fert | Growing | 34.50 | 187.49 | 11.79 | 64.06 |
| Mar | Apply Insect/Air | Growing | 8.44 | 195.93 | 2.88 | 66.94 |
| May | Knock Borders | Growing | 2.86 | 198.79 | 0.98 | 67.92 |
| Jun | Combine Harvest | Harvest | 53.33 | 252.12 | 18.22 | 86.14 |
| Jun | Haul | Harvest | 14.25 | 266.37 | 4.87 | 91.00 |
| Jun | Cut Stalks | Post Harvest | 6.61 | 272.98 | 2.26 | 93.26 |
| Misc. | Pickup Use | | 12.69 | 285.67 | 4.34 | 97.60 |
| | Operating Interest 6% | | 7.03 | 292.70 | 2.40 | 100.00 |
| | | | | | | |
| | TOTAL | | 292.70 | 292.70 | 100.00 | 100.00 |

| | | | | | | |
|---|---|---|---|---|---|---|
| **County:** | **Yuma** | | | | | |
| **Crop:** | **Head Lettuce** | | | | | |
| **Tot. Variable Cost:** | **$3,423.49** | | | | | |
| **Month** | **Operations** | **Class** | **Cost** | **Running Total ($)** | **% of Total Var. Cost** | **Running Total (%)** |
| July | Rip | Lnd Prep | 18.54 | 18.54 | 0.54 | 0.54 |
| July | Disk | Lnd Prep | 13.15 | 31.69 | 0.38 | 0.93 |
| July | Laser Level | Lnd Prep | 17.87 | 49.56 | 0.52 | 1.45 |
| July | Make Borders | Growing | 0.48 | 50.04 | 0.01 | 1.46 |
| July | Preirrigate | Growing | 6.39 | 56.43 | 0.19 | 1.65 |
| July | Soil Fertility | Growing | 3.00 | 59.43 | 0.09 | 1.74 |
| July | Dust Control | Growing | 4.91 | 64.34 | 0.14 | 1.88 |
| Aug | Apply Fert/Ground | Growing | 114.91 | 179.25 | 3.36 | 5.24 |
| Aug | Apply Herbicide/Ground | Growing | 129.43 | 308.68 | 3.78 | 9.02 |
| Sep | List | Lnd Prep | 5.34 | 314.02 | 0.16 | 9.17 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Aug | Pre-Shape | Lnd Prep | 7.56 | 321.58 | 0.22 | 9.39 |
| Aug | Shape Beds | Lnd Prep | 66.46 | 388.04 | 1.94 | 11.33 |
| Sep | Plant | Lnd Prep | 130.12 | 518.16 | 3.80 | 15.14 |
| Sep | Bird Control | Growing | 6.10 | 524.26 | 0.18 | 15.31 |
| Sep | Set Sprinklers | Growing | 5.02 | 529.28 | 0.15 | 15.46 |
| Sep | Irrigate/Sec Sys | Growing | 6.97 | 536.25 | 0.20 | 15.66 |
| Sep | Apply Insecticide/Air | Growing | 32.51 | 568.76 | 0.95 | 16.61 |
| Sep | Field Scouting | Growing | 90.00 | 658.76 | 2.63 | 19.24 |
| Oct | Apply Insecticide/Ground | Growing | 33.82 | 692.58 | 0.99 | 20.23 |
| Oct | Apply Insecticide/Ground | Growing | 54.94 | 747.52 | 1.60 | 21.84 |
| Sep | Irrigate/Run Fertilizer | Growing | 13.75 | 761.27 | 0.40 | 22.24 |
| Sep | Remove Sprinklers | Growing | 5.02 | 766.29 | 0.15 | 22.38 |
| Sep | Make Ditches | Growing | 2.39 | 768.68 | 0.07 | 22.45 |
| Oct | Irrigate/Run Fertilizer | Growing | 71.74 | 840.42 | 2.10 | 24.55 |
| Oct | Thinning | Growing | 100.00 | 940.42 | 2.92 | 27.47 |
| Oct | Cultivate | Growing | 22.53 | 962.95 | 0.66 | 28.13 |
| Oct | Apply Fungicide/Ground | Growing | 52.38 | 1015.33 | 1.53 | 29.66 |
| Oct | Apply Insect/Ground | Growing | 11.21 | 1026.54 | 0.33 | 29.99 |
| Oct | Apply Insect/Air | Growing | 33.57 | 1060.11 | 0.98 | 30.97 |
| Oct | Irrigate/Run Fertilizer | Growing | 21.94 | 1082.05 | 0.64 | 31.61 |
| Oct | Hand Weeding | Growing | 100.00 | 1182.05 | 2.92 | 34.53 |
| Oct | Apply Insect/Ground | Growing | 26.60 | 1208.65 | 0.78 | 35.30 |
| Nov | Knock Borders | Growing | 0.48 | 1209.13 | 0.01 | 35.32 |
| Nov | Knock Ditches | Growing | 0.80 | 1209.93 | 0.02 | 35.34 |
| Nov | Harvest, Load and Haul | Harvest | 2167.20 | 3377.13 | 63.30 | 98.65 |
| Dec | Disk Residue | Lnd Prep | 6.57 | 3383.70 | 0.19 | 98.84 |
| Misc. | Pickup Use | | 21.04 | 3404.74 | 0.61 | 99.45 |
| | Operating Inerest 6% | | 18.75 | 3423.49 | 0.55 | 100.00 |
| | | | | | | |
| | TOTAL | | 3423.49 | 3423.49 | 100.00 | 100.00 |

# Tree-ring records inform water management decisions

## Workshop strives for better integration of past with present



by Dustin Garrick and Kathy Jacobs

Water managers seeking new decision support tools and the scientists developing them congregated May 5 in Tucson to discuss how looking at the past may help inform future water planning efforts.

The workshop brought together key western water managers and paleoclimate researchers—those who use tree rings and other natural records to reconstruct what the climate was like hundreds or even thousands of years ago. Participants were specifically looking at how to incorporate dendrohydrology information into water planning. Dendrohydrology involves using tree ring qualities, typically the width of the annual growth rings, to estimate hydrological values, such as the annual streamflow of a specific river.

Among the outcomes of the meeting were a long list of research and collaborative opportunities, expanded interest in historic flow reconstructions on the part of water managers, and some lessons learned about how to structure meetings to encourage conversations across the perceived gulf between scientists and water managers.

Recent episodes of prolonged drought have functioned as a wake-up call for water supply managers seeking to satisfy demands in the context of water supply uncertainty and variability. Though most of the Southwest has had a wet winter, the severity of recent drought conditions is still fresh in residents' minds, and the low water levels in the Colorado reservoirs are a constant reminder that the drought is likely not over yet.

Meanwhile, conditions in the Pacific Northwest are very dry. The water managers in the room clearly understood the importance of having better climate information, especially in providing context for long-term infrastructure decisions and for drought planning.

The conference reflected the increasing interest in paleoclimate information, such as tree-ring based streamflow reconstructions, for use in water management and reservoir storage operations. Paleoclimate research and hydrologic reconstructions can aid water managers by extending the historical record of streamflow and other key water planning parameters—such as temperature—beyond the instrumental record, which covers approximately the past 100 years.

The lead workshop organizers were Connie Woodhouse of the National Oceanic and Atmospheric Administration (NOAA) Paleoclimatology Program, and Robert S. Webb of NOAA. They were joined by co-organizers from two NOAA-funded projects: the Western Water Assessment and the Climate Assessment for the Southwest (CLIMAS), in conjunction with the University of Arizona's Laboratory of Tree-Ring Research and UA's Water Resources Research Center. CLIMAS hosted the conference with funding from NOAA. The meeting advanced two overarching goals: broadening the use of paleoclimatic data and expanding the application of these data in water management contexts.

**Water Management**

Water planning needs and priorities took center stage from the outset with presentations by water managers who have incorporated paleoclimatic reconstructions into their planning processes. They recounted experiences integrating paleoclimate research into water resource planning.

Denver Water is working to use tree-ring records in tandem with their water supply simulation model to estimate the occurrence, frequency, and intensity of drought in the Colorado and Platte River basins, according to Steve Schmitzer, the head of water resource analysis. Tree-ring reconstructions have provided the agency with an enhanced understanding of streamflow and water demands during drought periods.

In Arizona, the recent drought coupled with the findings of tree-ring reconstructions have prompted water managers at the Salt River Project to consider long-term drought in planning activities, noted Charlie Ester, manager of the Phoenix-based agency's water resource operations.

SRP has linked with UA researchers from the Laboratory of Tree-Ring Research to investigate simultaneous drought in the Salt River and Colorado River basins. The agency was surprised that preliminary findings show that synchronous drought in their two water supply sources are more common than was previously thought. This is not good news for SRP, and it has motivated development of new strategies to prepare for potential water supply shortfalls caused by broad regional drought events.

Ester concluded that the question, "Is the drought over?" may not be particularly relevant. Even if this drought is over, there will definitely be another one in the future, he pointed out.

"We always get alternating periods of wet and dry years, so we need to start planning for worst-case scenarios now." Ester said.

**continued on page 3**

# Paleo meeting, continued

Ben Harding, principal engineer at Hydrosphere Resource Consultants presented on the potential benefits and lingering challenges of applying tree-ring and other paleoclimate research. He noted that water managers need to make decisions about the future, and paleohydrology information (for example, Figure 1) can help by providing a "surrogate for experience that tends to show you the large-scale structure of wet and dry periods."

However, like others, Harding warned that looking at such records does not allow predictions of specific future conditions, in part because conditions are changing in the context of global warming. Climate change scenarios predict average temperatures in the West will continue to rise in the foreseeable future because of the ongoing input of greenhouse gases from cars, industry, and land use changes. The warming has hydrological impacts, such as a tendency toward earlier melting of the mountain snow that sustains western rivers.

Harding also identified attributes of paleohydrologic data that have prevented wider adoption and application. For example, tree-ring reconstructions are often hard to connect to specific management decisions because the information is not available in locations where it is needed for water management. Often the measured data at key gauges do not have long-term, continuous records. In some cases the records are also less accurate than what is needed for high-quality calibration of the trends. Streamflow gauges may not be located appropriately to correlate to available tree-ring data, Harding noted.

The focus on water resource planning needs continued in a panel discussion involving high-level water managers from five states. The participants spanned the gamut of responsibilities, from reservoir operations at the Bureau of Reclamation to drought planning in New Mexico. The panel was asked how paleoclimate information has been and could be utilized by managers. Though several managers pointed out that they do not currently use tree ring information, all indicated that they were interested in doing so.

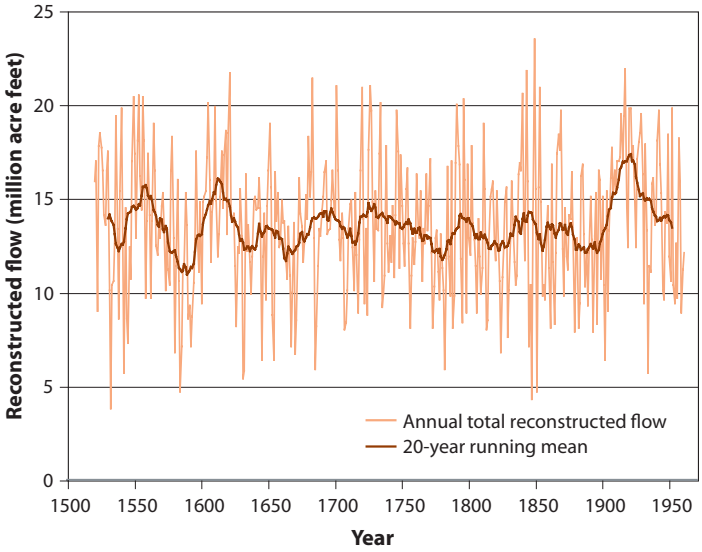



**Figure 1.** A 442-year record of Colorado River streamflow reconstructed from tree-ring evidence shows that variability is the norm, but high-flow or low-flow years often cluster together to span decades. The values are given in million of acre-feet from 1520 through 1961 and estimate streamflow throughout the Colorado River's 246,000-square-mile basin. Values are derived from tree-ring widths that were calibrated with U.S. Bureau of Reclamation records since 1906 based on gauged flow at Lee's Ferry, Arizona. Some of the scientists at the workshop are preparing an updated version of this record that extends into recent years. Source: Meko et al. 1995. *Water Resources Bulletin,* 31:789–801.

One theme that emerged from the panel discussion was the need to manage water resources in the context of uncertainty and to accommodate the role of politics and political pressure in the application of scientific findings.

"Every decision is filtered through the political process, and this must be added to the science to come up with the correct method," noted Don Ostler, executive director of the Upper Colorado River Commission.

The notion of triggers—as indicators of drought conditions and water supply variability—also produced a lively discussion between scientists and managers. Water managers expressed the need for triggers that induce specific management procedures and operational measures. This provides a measure of insulation, separating them from the political pressures that are always looming in the water arena.

**Paleoclimate Science**

The morning concluded with a presentation session by paleoclimate scientists to identify how ongoing research in the Colorado and Platte River basins can support water management decisions.

Many different Colorado River streamflow reconstructions, using varied statistical approaches, show good agreement with regard to the major periods of high and low flow, according to findings presented by David Meko, an associate research professor at the UA Laboratory of Tree-Ring Research. However, a comparison of Colorado River streamflow reconstructions showed significant differences in the precise volume of reconstructed streamflow.

Meko also presented work in progress, which shows that the average volume of flow at Lee's Ferry may actually be higher than the 13.5 million acre-feet that is frequently cited as the long-term average flow based on tree-ring records. However, even this higher long-term average is less than the average used in appropriating Colorado River water. Thus, the most up-to-date science still shows that the Colorado is over-appropriated.

The morning session laid the groundwork for a series of breakout groups in

**continued on page 4**

# Paleo meeting, continued

the afternoon. Scientists and managers convened to identify potential arenas for incorporating tree-ring and other paleoclimate research in water management settings. These breakout groups highlighted the need for enhanced outreach and communication with policymakers to assuage concerns about the level of uncertainty and variation among paleoclimate reconstructions. Water managers also urged further validation of the connections between tree-ring information and streamflow, despite strong concurrence among the scientists that their findings are statistically valid.

Water managers and scientists were eager to exchange ideas in the breakout session. These conversations pointed to relatively easy opportunities to enhance integration of paleoscience into water planning as well as more ambitious proposals for collaborative projects. Scientists and managers realized, for example, that there is a great need to publish findings in publications commonly read by water managers, instead of in scientific journals—the usual practice by paleoscientists. Another idea was to use a National Academy of Sciences panel to develop standardized research methods and criteria that could offer politicians and water managers a seal of approval to help justify the use of paleoclimate information.

The meeting culminated with an overview by co-organizer Kathy Jacobs that synthesized the conference into a set of core messages. Paleoclimate reconstructions have provided a critical long-term frame of possible water supply scenarios that significantly broadens the perspective of water managers, she noted. Understanding the full range of historic climate conditions allows comparison with conditions experienced during the careers of current water managers, Jacobs surmised. Long-term instrumental records show the period from about the 1970s through the mid-1990s was relatively wet, so our idea of "normal" may be skewed. In spite of the variation among tree-ring reconstructions, the studies do tell consistent stories about the fluctuations from high- to low-flow years, as well as long-term drought.

Jacobs, who is the deputy director for the UA Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA), also noted that the implications of drought are regionally specific, and paleoclimate information allows us to have a view of the synchroneity of droughts and implications for watersheds at various scales. There is a need to have such information tailored to individual water supply systems.

Managers at the workshop underscored the need for a better understanding of the nature and source of uncertainty, and the need to develop paleoclimate data that can be tailored to specific decisions, such as the Colorado River water supply shortage negotiations. Among specific data needs, water managers seek improved estimation of the "natural" flows—those adjusted for reservoir operations and other depletions—that feed water supply planning and modeling efforts, as well as increased focus on accurate gauging of flows.

Workshop participants also suggested further evaluation of the role of soil moisture in affecting tree ring data, since soil moisture processes may dampen or delay the effect of climate on tree growth. In addition, they noted a need to focus on communication of the findings of paleoclimate research so that it reaches decisionmakers at the right time and in an accessible format. It is particularly important to put the historic information in the context of the growing population in the Southwest and increasing demand for water supplies, since these factors may overwhelm the climate signal in making reservoir operation decisions.

The workshop generated substantial interest in future projects. Two suggestions that workshop organizers are eager to follow through on are the development of an interactive paleohydrology data and analysis web tool, and the development of workshops and training sessions that bring paleohydrology to an audience of water professionals and decision makers.

Working together, participants agreed, scientists and resource managers can use paleohydrological research and analyses to help water resources decisionmakers develop better worst-case scenarios, and to understand the geographic scales of multi-year periods of low-and-high flows. With adequate funding and time, tree-ring scientists should be busy responding to water managers' suggestions for developing reconstructions of flows from unregulated high-elevation stream gauges, Colorado River tributaries, such as the Green River, and examining spring temperature and snowpack—climatic keys to streamflow during the season of high water demand.

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### Resources on the Web

- Conference webpage (hosted by CLIMAS)
  http://www.ispe.arizona.edu/climas/conferences/CRBpaleo/index.html
- NOAA Paleoclimatology Program
  http://www.ngdc.noaa.gov/paleo/paleo.html/
- Laboratory of Tree-Ring Research, University of Arizona
  http:// www.ltrr.arizona.edu/

## Water Management on the Colorado River: From Surplus to Shortage in Five Years

***Dustin Garrick*** *– University of Arizona and*
***Kathy Jacobs*** *– Arizona Water Institute*

On Jan. 16, 2001, then-Secretary of Interior Bruce Babbitt approved a set of rules to manage surplus water supplies in the Colorado River Basin. These Interim Surplus Guidelines (ISG) were motivated by the other basin states' desire to curb water use by California, which had exceeded its allocation of river water for many years. The new rules provided a way of gradually enforcing the state's water allocation before water shortages emerged as a more urgent threat under future water use scenarios.

Few imagined the transition from surplus to shortage planning would occur so soon, as basin-wide storage dropped from 94 to 50 percent of capacity from 1999 to 2004 due to the combination of increased demand and five consecutive years of below-average inflow into Lake Powell. Despite the river's notorious over-allocation, this rapid reservoir decline threatened to diminish hydropower production and led to the first-ever water shortage in the basin.

In 2000, the U.S. Bureau of Reclamation utilized its long-range planning river operations model, the Colorado River Simulation System, to project future reservoir levels under different surplus alternatives. Because the five-year dry period from 1999 to 2004 has no precedent in the instrumental streamflow record, the model projections did not simulate any water supply scenarios that resembled the actual reservoir declines that occurred from January 2001 to April 2005, when Lake Powell hit its 37-year low.

### Striving for Consensus on Shortage

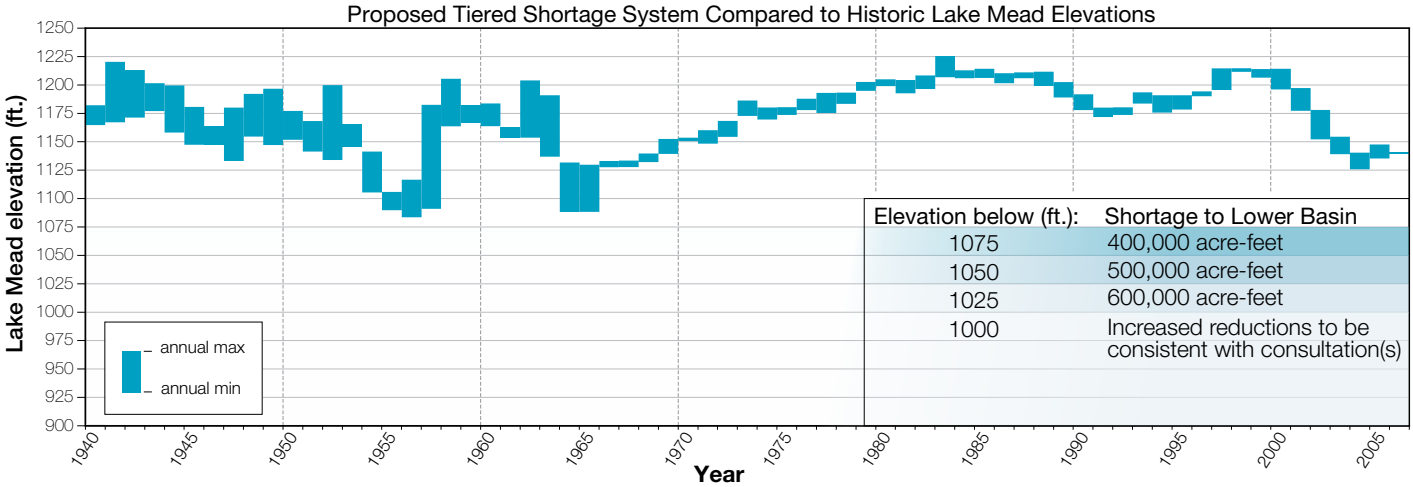
By spring 2004, declining reservoir storage prompted then-Secretary of Interior Gale Norton to urge the seven Colorado River Basin states to begin informal discussions about shortage to avert crisis-driven decisions. The ensuing negotiations have forced Colorado Basin water managers and users to reconsider elements of the ISG and several other long-standing legal, operational, and water-use issues. In June 2005, Norton initiated a public process in conformance with the National Environmental Policy Act (NEPA) to develop both shortage guidelines and management criteria for coordinating operations of lakes Powell and Mead during low-reservoir conditions. As part of the planning process, Reclamation is preparing an Environmental Impact Statement (EIS) for a range of alternative operating scenarios (see timeline at right).

### Costly Litigation Temporarily Averted

The NEPA process has advanced toward a shortage plan that could avert costly litigation among the states. On Feb. 3, 2006, all seven basin states approved a preliminary shortage management proposal. This was the product of two years of public and closed-door technical meetings where operations and policy alternatives were examined using the Colorado River Simulation System.

The preliminary proposal attempts to juggle competing demands for the river water and avert a rupture of the complex legal and operational rules that are collectively referred to as the Law of the River. If approved, the shortage proposal would remain in effect through 2025 and would:

- Coordinate reservoir management in lakes Powell and Mead to protect Upper Basin reservoir capacity and hydropower production in Lake Powell during early years of low reservoir conditions, while providing some relief to the Lower Basin's reservoir capacity in Lake Mead during later phases of shortages.
- Administer a tiered system of escalating Lower Basin annual shortage volumes according to Lake Mead elevations (see table below).
- Discontinue use of the "partial domestic surplus" designation under the 2001 ISG guidelines, thereby preventing surplus water deliveries from Lake Mead when reservoir levels fall below 1,145 feet in elevation.




*Proposed tiered shortage system for the Lower Basin, showing the annual quantity of shortage proposed in the basin at various reservoir elevations, compared to historic elevations. The distribution of such shortages among Lower Basin states and Mexico is being discussed as part of ongoing negotiations. Source: Seven Basin States' Preliminary Proposal Regarding Colorado River Interim Shortage Operations, Feb. 3, 2006.*

- Delay discussions on "catastrophic" Lower Basin shortages (greater than 600,000 acre-feet per year). Such shortages would trigger a set of emergency consultations.
- Temporarily augment supplies for water-strapped Nevada to delay controversial Virgin River diversions.

This preliminary agreement bodes well for a consensus among the seven states, and it has already triggered changes to the scope of analysis for the NEPA process. Reclamation released an EIS scoping document on March 31, 2006, that expands the scope to consider a credit system that would provide Lower Basin states with a mechanism to store "intentionally created surpluses" in Lake Mead during relatively wet years for use during shortage conditions.

In Arizona, discussions regarding intrastate shortage issues continue because the junior priority of Central Arizona Project water during shortages makes the state relatively more vulnerable than the other basin states. Shortages in Arizona will require interpretations of water contracts to address competing priorities among Central Arizona Project water users and water users along the river. The next major step is for Reclamation to release its draft EIS in late summer 2006 in anticipation of a record of decision in December 2007.

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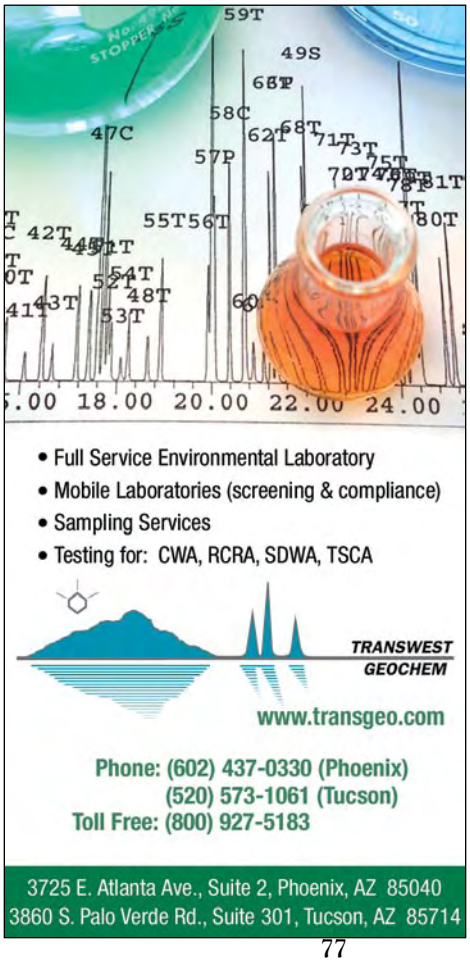
**Arizona's Shortage Planning History**

| | |
|---|---|
| Jan. 2001 | Former Secretary of Interior Bruce Babbitt signs Record of Decision for Interim Surplus Guidelines |
| May 2004 | Arizona Department of Water Resources (ADWR) initiates Shortage Sharing Stakeholder Workgroup |
| Dec. 2004 | Secretary Norton establishes April 2005 deadline for consensus plan from seven states |
| Apr. 2005 | Deadline passes without consensus shortage plan; on April 8, 2005, Lake Powell reaches 37-year low before rebounding slightly in summer 2005 |
| May 2005 | Secretary Norton conducts first-ever midyear review of the Lower Colorado River Annual Operating Plan and determines no changes are needed from "normal" operating plans |
| June 2005 | *Federal Register* notice announces start of public process to develop management protocol during "low reservoir conditions" |
| July 2005 | ADWR initiates series of five meetings in five weeks for Shortage Sharing Stakeholder Workgroup to review modeling scenarios and develop intrastate shortage sharing agreement |
| Sept. 2005 | *Federal Register* publishes notice of intent to prepare Environmental Impact Statement for shortage guidelines |
| Feb. 2006 | Seven states meet deadline for consensus preliminary proposal |
| Sept. 2006* | U.S. Bureau of Reclamation aims to release Draft Environmental Impact Statement on shortage guidelines |
| Dec. 2007* | Secretary of Interior intends to sign Record of Decision for shortage guidelines |

* Anticipated Dates



# Updated streamflow reconstructions for the Upper Colorado River Basin

Connie A. Woodhouse,[1] Stephen T. Gray,[2] and David M. Meko[3]

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[1] Updated proxy reconstructions of water year (October–September) streamflow for four key gauges in the Upper Colorado River Basin were generated using an expanded tree ring network and longer calibration records than in previous efforts. Reconstructed gauges include the Green River at Green River, Utah; Colorado near Cisco, Utah; San Juan near Bluff, Utah; and Colorado at Lees Ferry, Arizona. The reconstructions explain 72–81% of the variance in the gauge records, and results are robust across several reconstruction approaches. Time series plots as well as results of cross-spectral analysis indicate strong spatial coherence in runoff variations across the subbasins. The Lees Ferry reconstruction suggests a higher long-term mean than previous reconstructions but strongly supports earlier findings that Colorado River allocations were based on one of the wettest periods in the past 5 centuries and that droughts more severe than any 20th to 21st century event occurred in the past.

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## 1. Introduction

[2] The Colorado River, perhaps the most important regional source of surface water supply in the western United States, was the subject of the first tree ring based effort aimed at the quantitative reconstruction of streamflow records [*Stockton and Jacoby*, 1976]. The reconstruction of annual flows at Lees Ferry, which reflects conditions in the entire Upper Colorado River basin (Figure 1), contained several noteworthy features. The highest sustained flows in the entire record, 1520 to 1961, occurred in the early decades of the 20th century, a period that coincides with the negotiation of the 1922 Colorado River Compact and the resulting allocation of Colorado River flows. In effect, water that was not likely to be in the river on a consistent basis was divided among the basin states. In addition, the most persistent and severe drought occurred in the late 16th century, with flows during this period much lower than for any event in the 20th century.

[3] Two decades later, this landmark reconstruction was the basis for a series of studies that investigated the hydrologic, social, and economic impacts of a severe sustained drought in the Colorado River basin [*Young*, 1995]. These studies indicated that under the current Law of the River (the set of legal compacts and regulations that govern the Colorado River), a drought like the 16th century event in Stockton and Jacoby's record would greatly challenge the capacity of the Colorado River to meet water supply needs, and have significant impacts on Compact obligations.

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[4] Severe drought conditions in the Colorado River basin, coupled with a large increase in water use over the past two decades, have recently resulted in water demands that have outstripped natural inflows [*Fulp*, 2005]. Moreover, new water projects, additional management concerns such as endangered species, and large increases in population have altered the potential impacts of drought. These conditions have reinvigorated interest in reconstructions of Colorado River flow. *Stockton and Jacoby*'s [1976] original Lees Ferry reconstruction ended in 1961, which has made it difficult to assess recent droughts in a long-term context. In addition, reconstruction methods have evolved greatly in recent decades. *Hidalgo et al.* [2000] have shown that features of the Stockton and Jacoby reconstruction, including relative drought severity and duration, are sensitive to modeling methodology. Thirty additional years of gauge data, new and updated tree ring collections, and improved methodologies now enable a longer and more robust reconstruction of Colorado River streamflow. The purpose of this paper is to describe and analyze a recently generated set of updated streamflow reconstructions for Lees Ferry and other key gauges in the Upper Colorado River Basin.

## 2. Data and Methods for Reconstructions

### 2.1. Streamflow Data

[5] We selected four gauges in the Upper Colorado River basin for reconstruction: the Green River at Green River, Utah; Colorado River near Cisco, Utah; San Juan River near Bluff, Utah; and Colorado River at Lees Ferry, Arizona. The selected gauges represent flows in the three major subbasins as well as the total flow of the Upper Colorado Basin (Figure 1). The U.S. Bureau of Reclamation provided estimates of natural flows for these locations that span the years 1906 to 1995 (J. Prairie, personal communication, 2005). These flow values have been adjusted to account for human impacts through a combination of statistical and

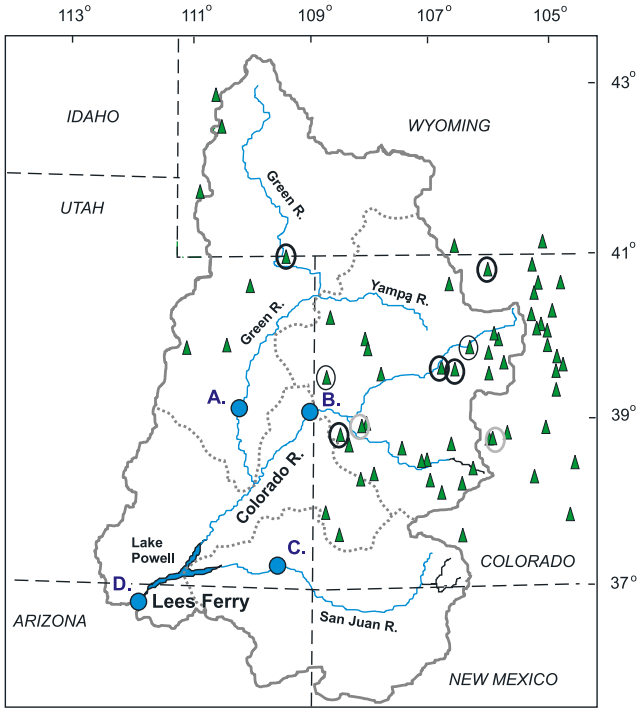


**Figure 1.** Location of gauges at Green River at Green River, Utah (A), Colorado River near Cisco, Utah (B), San Juan River near Bluff, Utah (C), and Lees Ferry, Arizona (D) (dots) and tree-ring chronologies (triangles). The upper Colorado River basin is outlined in a solid line, and the subbasins discussed are outlined by the dotted and solid lines (Green, Colorado with Yampa and Gunnison, and the San Juan basins). Tree ring chronologies used in Lees Ferry stepwise regression are circled; a thick black line indicates chronologies used in regression equations calibrated with both standard and residual chronologies, a gray line indicates chronologies used in the standard chronology calibration, and a thin black indicates chronologies used in the residual chronology calibration.

expert system approaches, but the records may still include some anthropogenic signals. Water year (October–September) flow data in millions of cubic meters (MCM) were examined graphically and statistically to assess variability, normality and the degree of persistence in the time series (Table 1). The water year flows are essentially normal, and all display a small amount of persistence at a lag of one year. The San Juan represents a considerably more arid region than the other two basins, as evidenced by the lower mean annual flow and higher coefficient of variation. The San Juan is also the only subbasin for which the first-order autocorrelation is not significantly greater than zero.

### 2.2. Tree Ring Chronology Network

[6] In much of the western United States, tree ring widths can provide a proxy for gauge records because the same climatic factors, primarily precipitation and evapotranspiration, control both the growth of moisture-limited trees and processes related to streamflow [*Meko et al.*, 1995]. Recent collections of new tree ring data and efforts to update older collections have produced a set of 62 moisture-sensitive tree ring chronologies in Colorado, southwestern Wyoming, and northeastern Utah that span the common interval from 1600 to 1997 (Figure 1 and Supplementary Data 1 in the online data set at http://www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html)[1]. Of the 62 chronologies, 17 are from ponderosa pine (*Pinus ponderosa*), 21 from Douglas fir (*Pseudotsuga menziesii*), 21 from pinyon pine (*Pinus edulis*), and three from limber pine (*Pinus flexilus*). Fifteen or more trees were typically sampled at each site using an increment borer and taking two cores from each tree. In the lab, cores were processed, crossdated, and measured using standard dendrochronological techniques [*Stokes and Smiley*, 1968; *Swetnam et al.*, 1985]. All ring width series were uniformly processed using the ARSTAN program as follows [*Cook*, 1985]. Measured series were standardized using conservative detrending methods (negative exponential/straight line fit or a cubic spline two thirds the length of the series) before using a robust weighted mean to combine all series into a single site chronology [*Cook et al.*, 1990]. Low-order autocorrelation in the chronologies that may, in part, be attributed to biological factors [*Fritts*, 1976] was removed, and the resulting residual chronologies were used in most of the subsequent analyses. However, the low-order autocorrelation in the gauge records was closely matched by persistence in the tree ring data. Consequently, the sensitivity to persistence in the tree ring data was tested in the Lees Ferry reconstruction by generating reconstruction models using both the standard (persistence retained) and prewhitened (persistence removed) chronologies. Because the number of series in these chronologies decreases with time, chronologies in the resulting reconstruction models were assessed with regard to subsample signal strength [*Wigley et al.*, 1984].

[7] Statistical analyses support the high quality and suitability of these chronologies for hydroclimatic reconstructions (Supplementary Data 1). The mean interseries correlation within each chronology averages 0.79, and mean sensitivity (average relative ring width difference from one ring to the next [*Fritts*, 1976]) averages 0.41. These statistics indicate the strong common signal between the trees that make up each chronology and the high degree of variability in ring widths from one year to the next. Both characteristics are consistent with strong tree ring sensitivity to climatic variability [*Cook and Briffa*, 1990].

### 2.3. Reconstruction Approaches

[8] Multiple linear regression, with predictors entered forward stepwise [*Weisberg*, 1985], was used to generate the reconstruction models. In an automated process such as stepwise regression, increasing the size of the potential predictor pool also increases the likelihood of a meaningless predictor entering the model by chance alone [*Rencher and Pun*, 1980]. To assess the sensitivity of the reconstruction to the size and makeup of the predictor pools, two alternative reconstruction approaches were tested for each gauge. First, the "full pool" approach used all chronologies significantly correlated ($p < 0.05$) with the gauge record as potential predictors. Correlations were evaluated over the entire

[1]Auxiliary material for this article contains upper Colorado streamflow reconstructions and three data tables and is available electronically from the World Data Center for Paleoclimatology, NOAA NCDC, 325 Broadway, Boulder, CO 80303, USA (URL: http://www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html).

**Table 1.** Metadata and Descriptive Statistics of Annual Flows

| Gauge Location[a] | Gauge Name | USGS ID | Basin Area, $10^6$ ha | Flow Statistics[b] | | | |
|---|---|---|---|---|---|---|---|
| | | | | Mean, $10^6$ $m^3$ | CV | Skew[c] | $r_1$ |
| A | Green R. at Green River, UT | 9315000 | 11.6161 | 6704 | 0.30 | 0.38 | 0.26[d] |
| B | Colorado R. nr Cisco, UT | 9180500 | 6.2419 | 8505 | 0.28 | 0.22 | 0.25[d] |
| C | San Juan R. nr Bluff, UT | 9379500 | 5.9570 | 2711 | 0.40 | 0.32 | 0.12 |
| D | Colorado R. at Lees Ferry, AZ | 9380000 | 28.9562 | 18778 | 0.28 | 0.15 | 0.25[d] |

[a]Gauge locations coded by letter are shown on map in Figure 1.
[b]Mean, coefficient of variation, skewness coefficient, and first-order autocorrelation computed from 1906–1995 annual (water year total) flows.
[c]None of the skewness coefficients are significantly different from zero at $\alpha = 0.05$.
[d]Significant of first-order autocorrelation based on one-tailed test, $\alpha = 0.01$.

gauge period (1906–1995) and over both early (1906–1950) and late (1951–1995) sets of years to ensure the stability of the correlation. A second approach, a "watershed-limited" approach, followed the same correlation rules, but the potential predictor set was restricted to chronologies within a 100 kilometer buffer around the watershed upstream from the gauge.

[9] Reduction of the predictor pool by a watershed boundary constraint was not feasible for the Lees Ferry gauge, as the watershed essentially encompasses all chronologies. The approach taken for that gauge was to reduce the predictor pool by principal components analysis (PCA). After first removing chronologies uncorrelated with Lees Ferry streamflow, a PCA was run on the correlation matrix of the chronologies for their full common period of overlap. *Mardia et al.* [1979, p. 244] suggest that in a regression context, the components having the largest correlations with the predictand, rather than the components with the largest variances, are best suited for retention. Accordingly, only those components significantly ($p<0.05$) correlated with streamflow were retained in the pool of potential predictors. The resulting pool has essentially been reduced to concisely express orthogonal modes of common variation in the tree ring data. Because each component is a linear combination of all tree ring chronologies correlated with streamflow, the PCA approach is relatively robust to nonclimatic influences (e.g., disturbance, insect outbreaks) at individual sites. For the Lees Ferry reconstruction, model sensitivity to the use of the standard versus the prewhitened chronologies was tested for both the non-PCA and PCA approaches described above. Validation statistics and features of the reconstructed time series were compared to assess sensitivity of results to the alternative model formulations.

[10] The strength of the regression models was summarized by the adjusted $R^2$ and $F$ level of the regression equation [*Weisberg*, 1985]. Possible multicollinearity of predictors was assessed with the variance inflation factor (VIF) [*Haan*, 2002]. A forward stepwise approach was used to enter predictors from the predictor pools, with threshold $F$ values for entry or removal of predictors. Variables were entered in order of their explained residual variance. As a guide, the $F$ level for a predictor was allowed to have a maximum $p$ value of 0.05 for entry and 0.10 for retention in the equation. Residuals for all regression models were inspected graphically for nonnormality, trend, autocorrelation, and obvious dependence on values of the predictors or predicted flows. Any of these conditions could indicate a need for data transformation. Residuals were tested for normality with the Lilliefors test [*Conover*, 1980].

[11] As a safeguard against model overfitting, the entry of predictors was terminated when it resulted in decreased validation accuracy. The reduction of error (RE) [*Fritts et al.*, 1990] and root mean squared error (RMSE) [*Weisberg*, 1985] were generated using two different calibration/validation schemes. In one scheme, a stepwise model was first fit to the full calibration period, recording the order of entry of predictors. The model was then fit to the first half of the data using the same predetermined order of entry for the predictors, and validated on the second half of the data. The calibration and validation halves were then exchanged and the process repeated. In the other validation scheme, leave-one-out cross validation [*Michaelsen*, 1987] was used to generate a single validation series. In both schemes, the RE and RMSE were calculated for each step and plotted to assess when the validation scores stopped improving. One last method of validation involved using the predictors selected by the stepwise regression process to run a linear neural network (LNN). LNN is an iterative model fitting process based on statistical bootstrapping techniques that was used here to assess bias in the explained variance. If the relationship between tree growth and climate is robust and stable, the results of LNN and stepwise regression should be equivalent [*Goodman*, 1996; *Woodhouse*, 1999].

## 3. Reconstructions

### 3.1. Full Pool Stepwise Regression Model Results

[12] Statistics for the initial full pool stepwise regression results using residual chronologies as predictors are listed in Table 2 in the first three lines under full pool models (subbasins) and the first line under the Lees Ferry models. The regression models all have highly significant F levels, account for between 72% and 81% of the variance of flow, and possess significant skill when applied to cross-validation testing. The predictor pools for the models contain between 24 and 38 chronologies, but the stepwise selection yields four to seven predictor chronologies in the final models.

[13] The residuals analysis indicated that normality of residuals could not be rejected (Lilliefors test, $p < 0.05$) for any of the series. Residuals for one gauge, Colorado-Cisco, showed borderline significance of autocorrelation at a 1-year lag. For three of the four gauges, residuals had a significant ($p < 0.05$) downward trend, suggesting greater tree growth than expected from flow in recent decades. A scatterplot indicated that the variance of residuals increased with the predicted values for the Colorado-Cisco. As neither square-

**Table 2.** Regression Statistics for Reconstruction Models[a]

| Gauge | Predictors in Pool | Number of Steps/Number of Predictors | $R^2$ | F level | RE | RMSE |
|---|---|---|---|---|---|---|
| | | *Full Pool* | | | | |
| GR/UT | 28 | 9/7 | 0.72 | 30.0 | 0.66 | 1149.2 |
| CO/Cisco | 38 | 5/5 | 0.77 | 54.0 | 0.73 | 1248.7 |
| SJ/Bluff | 24 | 4/4 | 0.73 | 56.7 | 0.70 | 589.7 |
| | | *Limited Pool* | | | | |
| GR/UT | 18 | 9/7 | 0.72 | 30.0 | 0.66 | 1149.2 |
| CO/Cisco | 32 | 4/4 | 0.73 | 57.7 | 0.69 | 1330.4 |
| SJ/Bluff | 8 | 3/3 | 0.67 | 58.8 | 0.64 | 640.6 |
| | | *Lees Ferry*[b] | | | | |
| Lees-A (res) | 31 | 7/7 | 0.81 | 48.7 | 0.76 | 2579.1 |
| Lees-B (std) | 30 | 7/7 | 0.84 | 61.2 | 0.81 | 2337.1 |
| Lees-C (res,PCA) | 3 | 1/1 | 0.72 | 226.9 | 0.71 | 2861.3 |
| Lees-D (std,PCA) | 4 | 1/1 | 0.77 | 294.7 | 0.76 | 2599.5 |

[a]Subbasin models based on full pool and watershed-limited pool of potential predictors and statistics for four alternative modeling choices for Lees Ferry record are given. Validation statistics RE and RMSE are based on cross validation.
[b]See Table 3 for definitions of models.

root nor log10 transformation of the flow record offered more than marginal improvement for that gauge, the decision was made to use the untransformed flows. The stepwise validation results indicated that strict adherence to the *F* enter and *F* remove criteria did not result in any obvious overfitting of the models. The numbers of steps and predictors chronologies for the four gauges are listed in Table 2. Regression coefficients are given in Supplementary Data 2 (http://www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html). Linear neural networks using the suite of predictors included in the regression equations yielded explained variance values that were the same as those from the regression approaches. An example of the comparison between a gauge record and a reconstruction is shown for Lees Ferry in Figure 2.

### 3.2. Sensitivity of the Reconstruction Models to Predictor Pool

[14] The predictor pool sensitivity tests apply only to the gauges on the Colorado-Cisco and San Juan, as the same predictors were selected from both pools for the Green River gauge. Limiting the pool by watershed boundary reduced the number of potential predictors from 38 to 32 chronologies for the Colorado-Cisco and from 24 to 8 chronologies for the San Juan (Supplementary Data 2). Stepwise regression for the Colorado-Cisco and the San Juan gauge yielded two and three predictors, respectively, in the full pool regression equation that were not in the limited pool equation. In these cases, as expected, the explained variance is reduced in the watershed-limited models. To address reconstruction sensitivity, reconstructions based on full pool and limited pools of predictors were compared with attention to critical precalibration periods, such as the well-known drought in the late 16th century [*Stockton and Jacoby*, 1976; *Gray et al.*, 2004; *Stahle et al.*, 2000]. A comparison of reconstructions for the San Juan and Colorado-Cisco from the two different models indicates only slight differences, particularly during periods of drought (Figure 3). On consideration of calibration/validation accuracy, the relative insensitivity of reconstructions to predictor pool reduction, and ability to reproduce statistical features of the observed record, we decided to adopt the full pool predictor subsets for the final subbasin reconstructions and analysis.

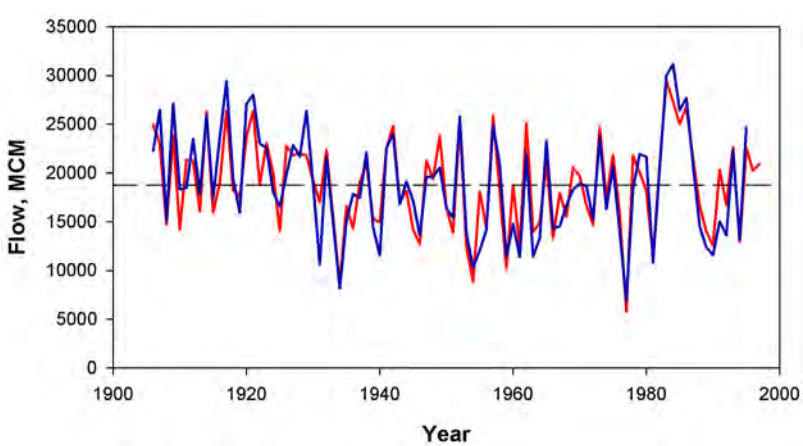


**Figure 2.** Comparison of observed and reconstructed streamflow, Lees Ferry gauge (blue line) and Lees-A reconstruction (red line), 1906–1997 (gauge to 1995).

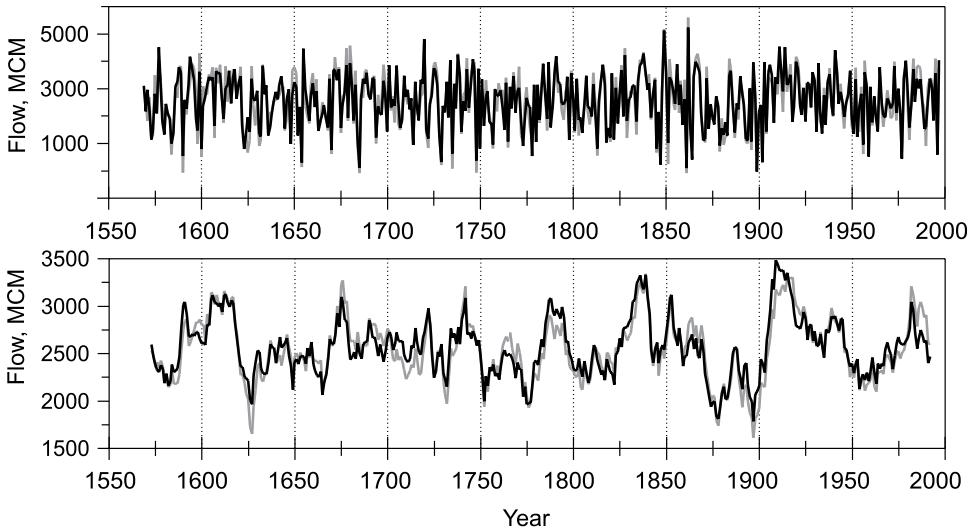


**Figure 3.** San Juan near Bluff, Utah, reconstructed streamflow, 1569–1997, from two models, full predictor pool (gray lines) and watershed-limited predictor pool (black lines): (top) annual values and (bottom) 10-year running average.

### 3.3. Sensitivity of the Lees Ferry Reconstruction to Modeling Approaches

[15] Reconstructions of Lees Ferry streamflow were tested using four different forms of the predictor tree ring data: residual chronologies (Lees-A, described in section 3.1), standard chronologies (Lees-B), principal components of residual chronologies (Lees-C), and principal components of standard chronologies (Lees-D). Exploratory analysis suggested 1490 as a reasonable start year for the reconstructions; of the original 62 chronologies, 31 residual chronologies and 30 standard showed significant correlations with annual streamflow and passed the screening test for time coverage to at least 1490 (Table 2). Stepwise regression on the standard chronologies (Table 2, Lees-B) yielded a reconstruction model with the same number of predictors (7) as for the residual chronology version, and a slight increase in F level and variance explained by regression (see Figure 1 for locations of predictor chronologies and Supplementary Data 2 for regression coefficients).

[16] The PCA indicated that the residual chronologies have somewhat more spatial structure than the standard chronologies (Supplementary Data 3, http://www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html). PC 1 is by far the most important component, accounting for 47% of the variance of the residual chronologies and 45% of the variance of the standard chronologies. For both sets of data, five PCs have eigenvalues exceeding 1.0, and these PCs account for a cumulative 69% (residual chronologies) and 68% (standard chronologies) of the tree ring variance.

[17] PC loadings on all chronologies are positive for PC 1 whether the PCA is on residual or standard chronologies. This pattern attests to the strong overriding common signal in tree growth over the Upper Colorado Basin. There appears to be some species dependence, with highest weights on *Pinus edulis* chronologies. Spatial organization in PCs 2-5 is most obvious for the residual chronologies: maps of loadings (not shown) indicate an east-west contrast in PC 2, a north-south contrast in PC 3, and spatial clustering in PCs 4 and 5.

[18] The predictor pools, based on significant correlation of PCs with streamflow, were PCs 1, 15 and 16 for the residual chronologies, and PCs 1, 17, 28, and 29 for the standard chronologies. Except for PC 1, a high percentage of tree ring variance accounted for by a PC did not imply strong correlation with streamflow.

**Table 3.** Statistics of Observed and Reconstructed Flow of Colorado River at Lees Ferry for 1906–1995 Calibration Period

| | Statistics[b] | | | | Running Means as Percentage of Normal[c] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Lowest | | | Highest | | |
| Series[a] | Mean | SD | Skew | r(1) | 1 year | 5 years | 20 years | 1 year | 5 years | 20 years |
| Lees-A | 18778 | 4787 | −0.14 | 0.04 | 31 | 79 | 89 | 157 | 139 | 111 |
| Lees-B | 18778 | 4885 | −0.26 | 0.22 | 28 | 76 | 83 | 151 | 142 | 115 |
| Lees-C | 18778 | 4526 | −0.52 | −0.05 | 25 | 81 | 90 | 141 | 130 | 108 |
| Lees-D | 18778 | 4679 | −0.47 | 0.31 | 28 | 73 | 83 | 148 | 139 | 115 |
| Obs. | 18778 | 5332 | 0.15 | 0.25 | 37 | 72 | 85 | 166 | 145 | 116 |

[a]Lees-A is reconstruction from residual chronologies, Lees-B is from standard chronologies, Lees-C is from PCs of residual chronologies, and Lees-D is from PCs of standard chronologies. Obs is the observed natural flow record (see text).
[b]Statistics are mean and standard deviation in MCM, skewness, lag 1 autocorrelation.
[c]Normal is defined as mean of observed flows for calibration period 1906–1995.

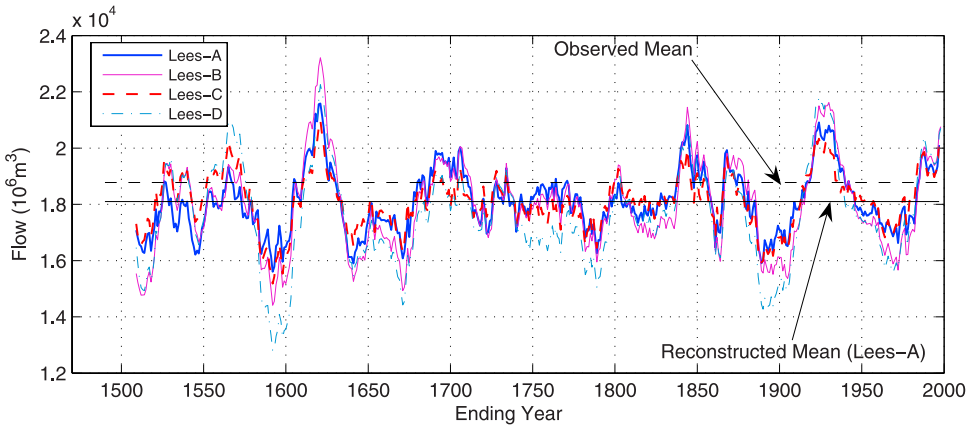


**Figure 4.** Reconstructed 20-year running means of Colorado River at Lees Ferry, Arizona, by alternative statistical models. Horizontal lines are the observed mean of the unsmoothed flows for the 1906–1995 calibration period (dashed line) and the reconstructed mean of unsmoothed flows for the entire (1490–1997) Lees-A reconstruction (solid line). See text and Table 3 for definitions of the models.

[19] In the stepwise procedure for both the residual and standard chronologies, only PC 1 entered as a predictor of flow (Table 2 and Supplementary Data 2). The final models (Table 2, Lees-C and Lees-D) account for 7–9% less variance of flow than the corresponding non-PCA models but, with just one predictor variable, have considerably higher F levels. Both PCA models verify well as indicated by the high cross validation RE statistics (Table 2). We repeated the PCA regression exercise with predictor pools made up of the PCs 1–5, rather than PCs screened by correlation with flow, and arrived at the same results, a final model with just PC 1 as the predictor.

[20] Descriptive statistics for the observed flows and the four alternative Lees Ferry reconstructions for the 1906–1995 calibration period are listed in Table 3. For the calibration period, the reconstructed and observed means are forced to be equal by the regression process, and differences in standard deviation simply reflect differences in proportion of variance explained by regression. The skew for all four reconstructions is opposite in sign from that of the observed flows, but given the short sample provided by the calibration period, only the skewness of Lees-C is significantly different from zero at $\alpha = 0.05$ [*Snedecor and Cochran*, 1989]. On the basis of Lilliefors test [*Conover*, 1980] the assumption of normality could not be rejected for any of the four reconstructions ($\alpha = 0.05$). A large contrast is seen in first-order autocorrelation of the two reconstructions based on residual chronologies versus the reconstructions using standard chronologies. The reconstructions by residual chronologies have essentially no first-order autocorrelation, while the observed flows and the reconstructions by standard chronologies are significantly positively autocorrelated ($p < 0.01$, one-tailed test).

[21] Annual observed flows range from 37% to 166% of the 1906–1995 mean. In general, for any reconstruction we expect departures from the calibration period mean to be underestimated due to compression of variance in regression modeling, but in Table 3 the lowest annual flows in all four reconstructions are lower than the lowest observed flow. This unexpected result might be due to the exaggerated negative skew of the reconstructions. In contrast, no reconstructed flow is as high as the highest observed flow. The 5-year running means are as expected, with neither highs nor lows as extreme as in the observed data. As expected when using residual chronologies, the 20-year running means are conservative, and the lows appear to be exaggerated by the reconstructions based on standard chronologies (Table 3).

[22] The four time series of smoothed full-length (1490–1997) Lees Ferry reconstructions track one another closely (Figure 4). All reconstructions indicate a long-term mean flow below the 1906–1995 observed mean. The long-term reconstructed mean ranges from 94.0% to 96.5% of the observed mean, and so is relatively insensitive to choice of model. If the standard error of an $m$-year mean of reconstructed values is assumed to be $1/\sqrt{m}$ times the root-mean square error of the annual reconstructed values (Table 2) and the errors are normally distributed, all four recon-

**Table 4.** Statistics of Reconstructed Flow of Colorado River at Lees Ferry, 1490-1997, and Observed Flow, 1906–1995[a]

| | Statistics | | | | Running Means as Percentage of Normal | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Lowest | | | Highest | | |
| Series | Mean | SD | Skew | r(1) | 1 year | 5 years | 20 years | 1 year | 5 years | 20 years |
| Lees-A | 18097 | 5555 | −0.30 | 0.04 | 11 | 63 | 83 | 167 | 142 | 115 |
| Lees-B | 17957 | 5616 | −0.21 | 0.29 | 11 | 56 | 77 | 167 | 156 | 124 |
| Lees-C | 18124 | 4990 | −0.32 | −0.00 | 13 | 66 | 81 | 172 | 130 | 112 |
| Lees-D | 17656 | 5193 | −0.19 | 0.34 | 14 | 50 | 68 | 170 | 143 | 119 |
| Obs. | 18778 | 5332 | 0.15 | 0.25 | 37 | 72 | 85 | 166 | 145 | 116 |

[a]Series and columns defined as in Table 3.

**Table 5a.** Interbasin Correlations of Observed and Reconstructed Flows: Correlation Matrices of Observed and Reconstruction Flow for the Period 1906–1995[a]

| | GRUT | COCI | SJBL |
|---|---|---|---|
| | *Observed* | | |
| COCI | 0.85 | | |
| SJBL | 0.55 | 0.77 | |
| Lees | 0.92 | 0.98 | 0.79 |
| | *Reconstructed* | | |
| COCI | 0.87 | | |
| SJBL | 0.71 | 0.84 | |
| Lees | 0.93 | 0.95 | 0.83 |

[a]GRUT, Green River at Green River; COCI, Colorado River near Cisco; SJBL, San Juan near Bluff; Lees, Colorado at Lees Ferry.

structed means are significantly ($\alpha = 0.05$) different than the observed mean.

[23] Depending on reconstruction model, the long-term standard deviation is greater than (non-PCA models) or less than (PCA models) the standard deviation of observed flows (Table 4). If climate were equally variable before and during the calibration period, compression of the variance in regression would tend to yield a long-term reconstruction with lower variance than that of the observed flows. The greater standard deviation for the non-PCA models implies more variable climate before the start of the calibration period than after. All four reconstructions are negatively skewed, but the assumption of zero skew can be rejected ($p < 0.05$, N = 508) only for the reconstructions from the residual chronologies (Table 4).

[24] Differences in first-order autocorrelation among models were noted for the 1906–1995 calibration period (Table 3), and those differences also apply to the long-term reconstructions (Table 4). A comparison of first-order autocorrelations of reconstructed data for the full reconstruction and the calibration period suggests the autocorrelation in the calibration period is representative of the long-term record. It is also evident, however, that the autocorrelation of the reconstructed flows from residual chronologies is biased low relative to that of the observed flows (Table 3). The impact of the disparity in first-order autocorrelations for model Lees-A was investigated by restoring the persistence to the reconstructed flow with an autoregressive model, and comparing the original reconstruction with the persistence-restored reconstruction. The two series were extremely similar, and although 2-year droughts were slightly less common and three-year slightly more common in the persistence-restored reconstruction, there were no distinct differences for longer droughts. The reconstructions from standard chronologies more accurately reflect the first-order autocorrelation of the observed record (Table 3). Model Lees-D is perhaps strongest in this regard because the reconstructed flows are slightly more autocorrelated than the observed flows. This is reasonable because the reconstruction errors are assumed to not be autocorrelated.

[25] Extreme n-year running means are quite similar for the alternative Lees Ferry reconstructions, but somewhat more extreme for the reconstructions using the standard chronologies (Table 4). Regardless of model, the lowest 1-year, 5-year and 20-year means for the full reconstructions are much below those in the observed flows. The lowest reconstructed 20-year means for all models are in the late 1500s (Figure 4; note that this drought is somewhat more severe in the standard chronology PCA model). In the standard chronology models, the highest reconstructed *n*-year means exceed those in the observed record, with the exception of 5-year means. Smoothed time series of the four reconstructions are in agreement in the exceptional wetness of the early 1900s (Figure 4). The implication is that a period of such sustained wetness had not occurred since the start of the 1600s.

[26] In summary, the above comparison shows that key features of the updated flow reconstructions for Lees Ferry are fairly robust to modeling choices. The models using the standard chronologies appear to more closely match the persistence in the gauge record, and the non-PCA version using standard chronologies (Lees-B) has the greatest calibration period accuracy as measured by regression $R^2$. On the other hand, the models based on standard chronologies overestimate the severity of multidecadal droughts (20-year means) in the calibration period, which is worrisome considering that the regression procedure itself tends to compress reconstructed values toward the calibration period mean. Smoothed time series plots (Figure 4) suggest the PCA reconstruction on standard chronologies (Lees-D) is somewhat of an outlier, and gives a worst-case scenario for the severity of extended droughts and wet periods. In view of the fact that the subbasin gauges were reconstructed using the residual chronologies and a non-PCA approach, for consistency of analysis we used the reconstruction version Lees-A as the baseline record in the subbasin analysis that follows.

### 3.4. Spatial Fidelity Among Gauges and Reconstructions

[27] The relationship between gauges within the Upper Colorado River basin, and how those relationships were preserved in the reconstructions, was evaluated by examining the shared variance between the set of gauge records and the set of reconstructions. Spatial relationships were then examined with regard to the magnitudes of flow from the subbasins and their relationship to the total Colorado River flow at Lees Ferry.

[28] In the gauge records, all flows are highly correlated ($r > 0.77$) except between the San Juan and the Green ($r = 0.55$), the most widely separated gauges (Table 5a). In the reconstructed flow records for the same time period (1906–1995), the same relationships are preserved between the Green, Colorado-Cisco, and Lees Ferry reconstructions. Correlations between the San Juan and the other reconstructions are somewhat inflated, particularly between the Green and San Juan (Table 5a). The relationships for the full

**Table 5b.** Interbasin Correlations of Observed and Reconstructed Flows: Correlation Matrix of Reconstructed Flows for the Period 1569–1997[a]

| | GRUT | COCI | SJBL |
|---|---|---|---|
| COCI | 0.87 | | |
| SJBL | 0.69 | 0.83 | |
| Lees | 0.93 | 0.96 | 0.82 |

[a]GRUT, Green River at Green River; COCI, Colorado River near Cisco; SJBL, San Juan near Bluff; Lees, Colorado at Lees Ferry.

**Table 6.** Percentage of Observed and Reconstructed Annual Flow at Lees Ferry Contributed by Subbasins

| | 3 Gauge Total | GRUT | COCI | SJBL |
|---|---|---|---|---|
| Observed, 1906–1995 | 95.5 | 35.8 | 45.4 | 14.2 |
| Reconstructed, 1906–1995 | 95.6 | 35.9 | 45.5 | 14.3 |
| Reconstructed, 1569–1997 | 96.3 | 35.7 | 46.7 | 13.9 |

reconstructions are quite similar to those for the period of the gauge records (Table 5b). The greater shared variance between the San Juan reconstruction and the other reconstructions, compared to the relationships in the gauge record, may be due to an absence of tree ring chronologies located within the San Juan River basin. The result of this may be a weaker representation of local basin variability.

[29] The observed flows from the three subbasins gauges, Green River, Colorado-Cisco and the San Juan account for nearly all (average of 95.5%) of the total water year flow observed at Lees Ferry from 1906–1995 (Table 6). Over the same years, the average values of contributed flows in the reconstructions are closely matched, as expected due to the regression process. Over the full common reconstruction period, 1569–1997, contributions are also very similar (Table 6). Figure 5 shows the variations in flow at the four gauges and the sum of the three subbasin flows over the full reconstruction period as 5-year running averages. The match between the three gauge sum and the Lees Ferry flow is good ($r = 0.98$, $p < 0.001$), though there are several periods when the sum appears to be somewhat less than Lees Ferry total flow (e.g., the 1630s and the last quarter of the 1600s, both periods of higher flows).

## 4. Long-Term Hydroclimatic Variability in the Upper Colorado River Basin

### 4.1. Frequency Characteristics of Reconstructed Flows

[30] We used a multitaper method (MTM) spectral analysis to examine the frequency characteristics of reconstructed flows at Lees Ferry and the three subbasins gauges [*Mann and Lees*, 1996]. MTM provides a robust means for isolating signal peaks from a time series that may contain both periodic and aperiodic behavior. The MTM spectrum for the Lees Ferry reconstruction (Figure 6a) shows that significant ($p < 0.05$) high-frequency variability in Upper Colorado River flows (2–7 years) is accompanied by a strong bidecadal peak centered around ~24 years. MTM also identifies a significant multidecadal peak around 64 years. Peaks similar to those in the two to seven year band at Lees Ferry are also present in the spectra for each subbasin (Figures 6b–6d). All of the subbasin reconstructions show significant bidecadal peaks, though relative power is reduced for the Green River gauge. The reconstructions for both the Colorado-Cisco and the San Juan show strong multidecadal peaks centered on ~64 years. Cross-spectral MTM reveals significant coherency across the subbasins at lower frequencies (Figure 7). Coherency and phasing of bidecadal and multidecadal peaks is particularly strong.

[31] The wavelet spectra for each of these reconstructed gauge records further highlights their coherence in the frequency domain (Figure 8). Wavelet analysis also shows marked nonstationarity in the strength of these signals through time. In particular each of the wavelet spectra are characterized by multidecadal variability (30–70 year) in the first two centuries followed by a period from the 18th through mid-19th centuries dominated by significant energy in the decadal to bidecadal bands. Beginning in the late 19th century, however, we see a return to significant multidecadal variability. These lower-frequency modes persist until the late 20th century, when the effects of zero padding likely reduce power in the multidecadal bands [*Torrence and Compo*, 1998].

### 4.2. Basin-Scale Flow Variability

[32] The Lees Ferry and subbasin streamflow reconstructions enable an examination of the spatial characteristics of long-term drought variability in the upper Colorado River basin. We first compared 5-year, 10-year, and 20-year averages of streamflow in the Lees Ferry reconstruction with averaged flows in the three subbasins to determine the degree of drought variability across the upper Colorado River basin. In general, there is a strong tendency for extreme low flows at Lees Ferry to be matched by extreme low flows in all three of the subbasins. Of the driest 5-year

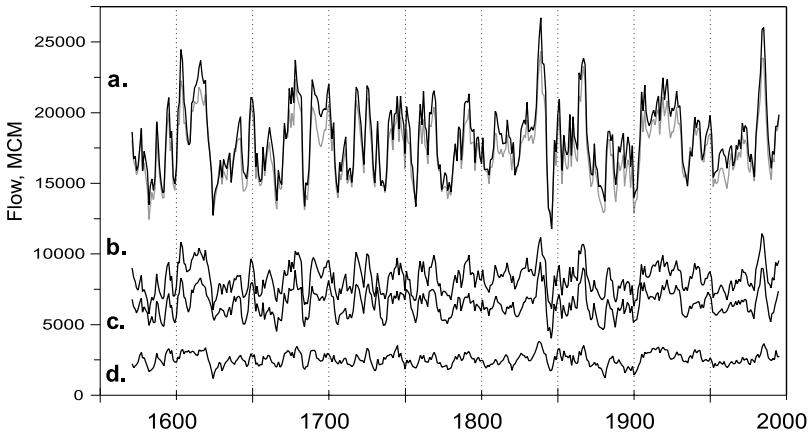


**Figure 5.** Five-year running averages of reconstructed annual streamflow, 1571–1995, for Lees Ferry, Arizona (black line a), the sum of the flow for the three reconstructions (gray line a), and the three subbasins, Colorado near Cisco, Utah (line b), Green River at Green River, Utah (line c), and San Juan River near Bluff, Utah (line d).

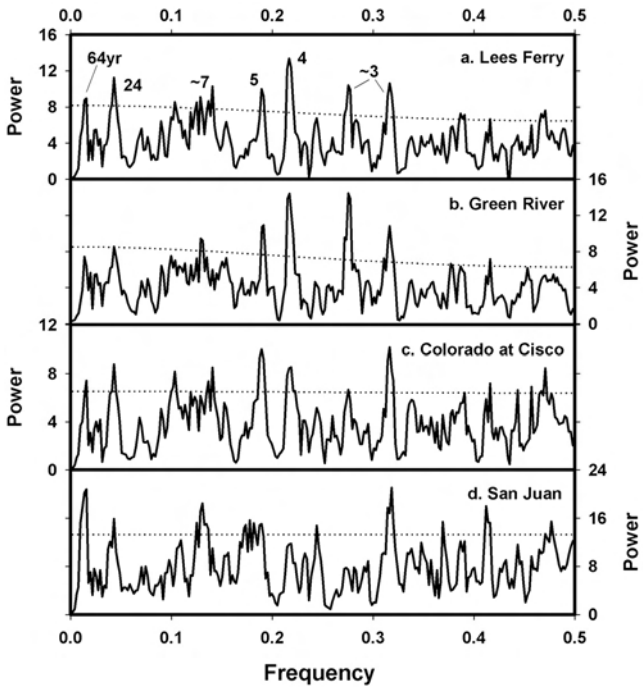


**Figure 6.** Multitaper method spectral analyses [*Mann and Lees*, 1996] of reconstructed flows for (a) the Colorado at Lees Ferry, Arizona, (b) the Green River at Green River, Utah, (c) the Colorado near Cisco, Utah, and (d) the San Juan near Bluff, Utah. All spectra cover the common period from 1569 to 1997. Peaks are shown versus the 95% confidence level (dotted line). These analyses were performed using a 3 × 2 pi taper under red noise assumptions.

periods (lowest 15% of flows) in the Lees Ferry reconstruction, none ranked above the driest tercile in the Colorado-Cisco reconstruction, which accounts for the greatest proportion of Lees Ferry flow. Two of driest Lees Ferry flow periods ranked in the middle tercile in the Green River reconstruction record (1728–1732, 1628–1632). There were nine periods in the San Juan reconstruction that fell within the middle tercile that were dry periods in the Lees Ferry record. Four of these periods occurred in the 1580s and 1590s, which is known regionally as an extreme drought throughout the western United States [e.g., *Stahle et al.*, 2000]. While there were some extremely dry years in the San Juan reconstruction over this period (e.g., 1590), this period was also marked by several wet years (e.g., 1589, 1595, 1599).

[33] Important regional variations do exist within extreme dry periods (Table 7). Rankings of 5-year averages show that the driest 5-year period in the Lees Ferry record, 1844–1848, was extremely dry in the Green and Colorado-Cisco records (driest and third driest, respectively), but was somewhat less extreme in the San Juan (17th driest). The second most extreme 5-year low-flow period in the Lees record, 1622–1626, was similarly dry in the Colorado-Cisco and San Juan records (second driest and driest, respectively), but to a much lesser extent in the Green (63rd driest). Regional variability in extreme low flows is also evident over longer timescales. The period 1622–1631 was the driest 10-year period in the Lees Ferry reconstruction. As in the 5-year periods, low flows in 1620s are less extreme in the Green River record, but are markedly low in both the San Juan and Colorado-Cisco records (ranks 71st, third, and sixth, respectively). In contrast, the Green River appears to be most strongly impacted by decadal-scale droughts in the 1870s and 1880s. As suggested above, the San Juan appears to be less sensitive to the low flows in the 1580s and 1590s, and this is evident at both 10-year and 20-year timescales. The 20-year period ending in 1592 is the driest such period in the Lees Ferry and Colorado-Cisco reconstructions, and the sixth driest in the Green reconstruction, but it was the 48th driest period in the San Juan reconstruction.

[34] Regional drought variability was also examined in the context of its impacts on Lees Ferry flows. Rankings for 10-year moving averages of flow in the three subbasins were divided into terciles. Periods when the value for one basin fell in the dry tercile while flow in another basin fell into the wet tercile, were tabulated (Table 8). Again, droughts tend be widespread, affecting, to some degree, all three subbasins simultaneously. However, in 15 of these 10-year periods, contrasting conditions exist between two basins. Most commonly (eight periods), high flows in the San Juan reconstruction coincide with low flows in the Green reconstruction. Dry conditions in the San Juan and wet in the Green are far less common (three periods). In two periods, the Green is dry while the Colorado-Cisco is wet, and there is one case each when the San Juan is wet and Colorado-Cisco dry and vice versa. The contrasting conditions in the pairs of subbasins appear to balance each other with respect to Lees Ferry flow for the most part, with Lees Ferry flow for these periods most often falling in the middle

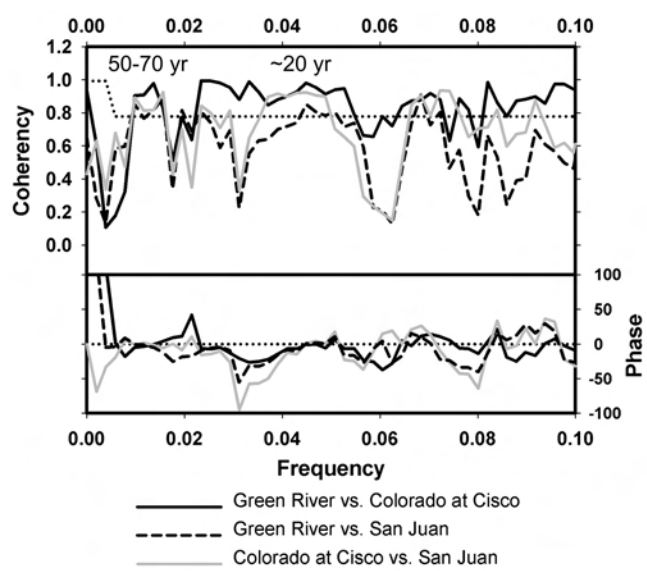


**Figure 7.** Multitaper method cross-spectral analysis [*Mann and Lees*, 1996] of reconstructed flows at the major subbasin gauges on the Green River at Green River, Utah; Colorado River near Cisco, Utah; and San Juan River near Bluff, Utah. (top) Coherency spectra plotted against the 95% confidence interval (dotted line). (bottom) Phasing of spectral peaks.

**Table 7.** Ranked Subbasin Flows During Lowest 5-year, 10-year, and 20-year Moving Averages of Reconstructed Flow at Lees Ferry[a]

| | | 5-year Average | | | | 10-year Average | | | | 20-year Average | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lees Rank | 5 year | GR Rank | CC Rank | SJ Rank | 10 year | GR Rank | CC Rank | SJ Rank | 20 year | GR Rank | CC Rank | SJ Rank |
| 1 | 1848 | 1 | 3 | 17 | 1631 | 71 | 6 | 3 | 1592 | 6 | 1 | 48 |
| 2 | 1626 | 63 | 2 | 1 | 1782 | 9 | 8 | 17 | 1593 | 7 | 2 | 82 |
| 3 | 1847 | 8 | 8 | 9 | 1592 | 5 | 3 | 57 | 1641 | 57 | 14 | 13 |
| 4 | 1846 | 3 | 12 | 54 | 1632 | 40 | 1 | 2 | 1889 | 2 | 9 | 5 |
| 5 | 1759 | 24 | 16 | 29 | 1781 | 11 | 9 | 12 | 1598 | 3 | 3 | 97 |
| 6 | 1686 | 11 | 6 | 22 | 1593 | 1 | 7 | 92 | 1890 | 1 | 15 | 20 |
| 7 | 1584 | 16 | 1 | 8 | 1883 | 3 | 25 | 4 | 1671 | 13 | 16 | 45 |
| 8 | 1883 | 7 | 36 | 2 | 1737 | 43 | 10 | 16 | 1638 | 52 | 55 | 28 |
| 9 | 1668 | 2 | 13 | 44 | 1879 | 4 | 26 | 18 | 1639 | 66 | 57 | 25 |
| 10 | 1902 | 10 | 5 | 3 | 1880 | 2 | 18 | 24 | 1640 | 77 | 64 | 21 |

[a]The ending years of the 10 lowest-flow periods at Lees Ferry are listed under "5 year," "10 year," and "20 year." Subbasin gauges are Green River at Green River (GR), Colorado near Cisco (CC), and San Juan near Bluff (SJ).

tercile. However, in four of the eight periods when Green River is low and the San Juan river is high, flow at Lees Ferry is in the driest tercile, and except for one of the eight periods, Lees Ferry flow is lower than the median. This suggests that low-flow conditions in the Green River can override wet conditions in the San Juan, and to some extent, moderate conditions in the Colorado-Cisco, to influence Lees Ferry flows. Greater sensitivity of Lees Ferry flow to the Green than to the San Juan is of course expected, given the much larger percentage of flow contribution from the Green (Tables 1 and 6).

[35] As shown in the spectral analysis (section 4.1), streamflow at Lees Ferry and the three subbasins also varies significantly over multidecadal timescales. To highlight this lower-frequency variability, each of the reconstructions was smoothed with a 50-year cubic spline (Figure 9). The

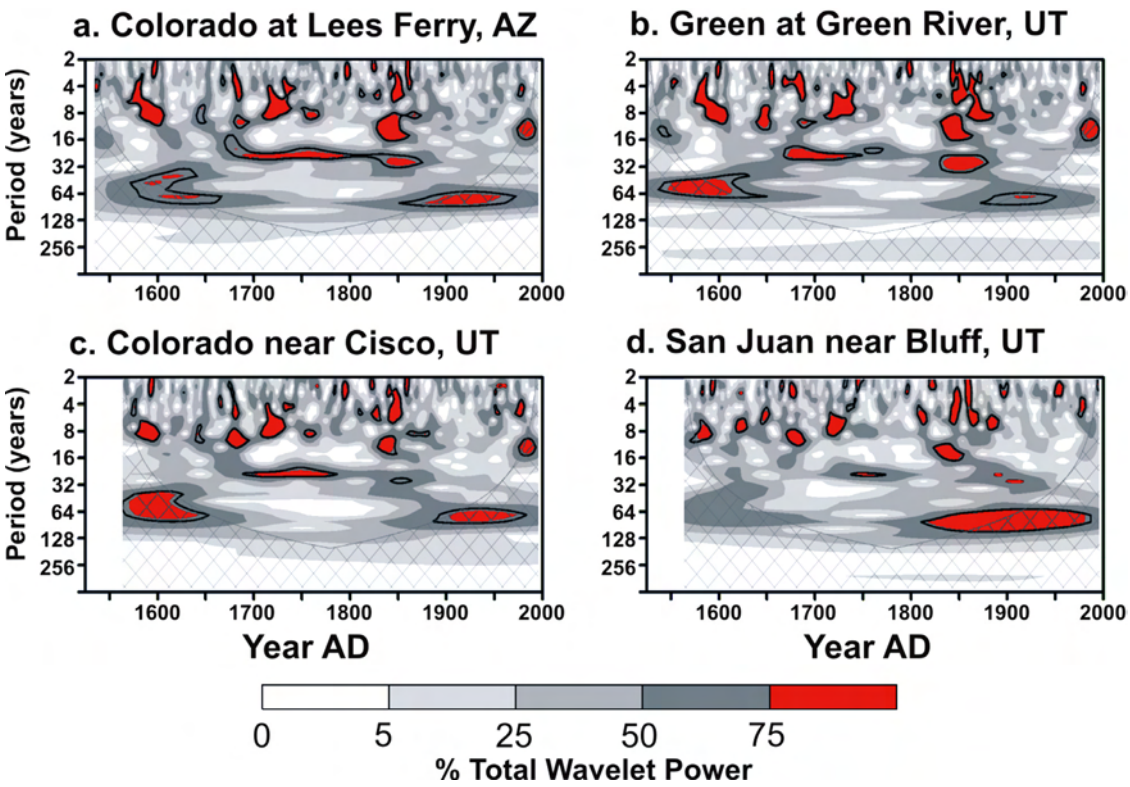


**Figure 8.** Wavelet power spectra of reconstructed flows for (a) the Colorado River at Lee's Ferry, Utah, (b) Green River at Green River, Utah, (c) Colorado River near Cisco, Utah, and (d) San Juan River near Bluff, Utah. A derivative of the Gaussian wavelet ("Mexican Hat"; see *Torrence and Compo* [1998]) was used under red noise assumptions, and each reconstruction was padded with zeros to avoid wraparound effects. Black contours in the power spectra represent the 95% confidence level compared to red noise. The cone-shaped net shows portions of the spectrum where power may be reduced through the effects of zero padding [*Torrence and Compo*, 1998]. All spectra cover the common period from 1569 to 1997.

**Table 8.** Terciles and Percentiles of 10-year Moving Average Reconstructed Flow at Lees Ferry During Periods of Contrasting Flow Anomalies in Subbasins[a]

| Contrast | Lees Flow Tercile | Lees Flow Percentile |
|---|---|---|
| Green dry/San Juan wet | | |
| 1597 | middle | 0.546 |
| 1600 | dry | 0.171 |
| 1674 | dry | 0.283 |
| 1743 | middle | 0.406 |
| 1856 | middle | 0.475 |
| 1941 | dry | 0.276 |
| 1942 | dry | 0.320 |
| 1943 | middle | 0.363 |
| Green wet/San Juan dry | | |
| 1735 | middle | 0.463 |
| 1766 | middle | 0.658 |
| 1774 | middle | 0.518 |
| Green dry/Colorado wet | | |
| 1818 | middle | 0.615 |
| 1823 | middle | 0.489 |
| San Juan wet/Colorado dry 1859 | middle | 0.499 |
| San Juan dry/Colorado wet 1820 | middle | 0.610 |

[a]Year listed is last of 10.

smoothed time series display a pattern of high magnitude variations in the 16th and 17th centuries and the 19th and 20th centuries, with dampened variability centered on the 18th century. The driest multidecadal period in the Lees Ferry reconstruction occurs in the late 16th century. The low-flow period at the end of the 19th century shares a similar magnitude. In this multidecadal context the 1950s drought is also notable as the 4th lowest flow period at Lees Ferry. Generally high-flow regimes occurred across the basin in the early 17th and early 20th centuries. The most recent decades of the reconstruction were also quite wet. As in the case of the multiyear and decadal flow regimes discussed above, the magnitude of departures for these multidecadal flow regimes varies somewhat across the basin. This is particularly true for the early 1700s through the mid 1800s, which is the period when the wavelet analyses show a significant loss of multidecadal power in the basin. However, the timing and duration of multidecadal flow regimes is markedly coherent across the Upper Colorado River Basin.

### 4.3. Comparison with Previous Lees Ferry Reconstructions

[36] Because of the central importance of the Lees Ferry record to the allocation of Colorado River water supply, it is important that the reconstruction be as accurate as possible, and that the uncertainty be appreciated. The discussion in section 3.3 dealt with uncertainty due to modeling choices: the use of standard versus residual chronologies and the decision to use individual chronologies or chronologies reduced by PCA in the regressions. Previous reconstruction efforts [*Stockton and Jacoby*, 1976; *Hidalgo et al.*, 2000] not only used different modeling procedures from ours, but also a different tree ring network and a much shorter calibration period. In this section we compare our updated reconstructions, versions Lees-A and Lees-D, with reconstructions by *Stockton and Jacoby* [1976] and *Hidalgo et al.* [2000]. We refer to these two previous reconstructions as SJ1976 and HDP2000. The comparison focuses on two statistics: the long-term mean annual flow, and the most severe sustained drought as measured by the lowest reconstructed 20-year moving average of flow. Lees-A is our model using regression of flow on residual chronologies. Lees-D is our model using regression of flow on PCs of standard chronologies. Those two versions were selected for the comparison because they represent the most conservative (wettest) and least conservative (driest) of the alternative reconstructions from the updated chronologies (see section 3.3).

[37] Time series plots of smoothed reconstructions (Figure 10) generally agree in timing of highs and lows, but disagree considerably on the magnitude of some flow anomalies. The plots for the updated reconstructions generally show wetter conditions than the previous reconstructions. HDP2000 represents the driest scenario, with greatly amplified low-flow features in the late 1500s, late 1700s and near 1900. Much less disagreement among the four reconstructions is evident in the calibration period than in the precalibration period.

[38] Selected calibration and reconstruction statistics for the four models are listed in Table 9. Flow statistics are given in units of both billion cubic meters (BCM) and million acre-feet (MAF) to facilitate comparison with previous published studies. Note that the reconstructions differ considerably in calibration period as well as in the number of tree ring chronologies on which the final reconstructions depend. Agreement of the reconstructions in the calibration period (Figure 10) is not surprising as all four models have high $R^2$ values (Table 9). Perhaps the most striking disagreement in the models is the magnitude of the late 1500s drought (the period of the lowest 20-year mean), which is estimated at 11.2 BCM (9.1 MAF) by HDP2000 and 15.6 BCM (12.6 MAF) by Lees-A. The updated reconstructions suggest the long-term mean annual flow is not as low as previously estimated. Our driest updated reconstruction model (Lees-D) gives a long-term mean of 17.6 BCM (14.3 MAF), which is some 0.9 BCM (0.8 MAF) higher than the original estimate by *Stockton and Jacoby* [1976].

[39] Differences in the reconstructions are undoubtedly related to differences in the basic data and the statistical models used for reconstruction. The most obvious data difference between this and past efforts would be that

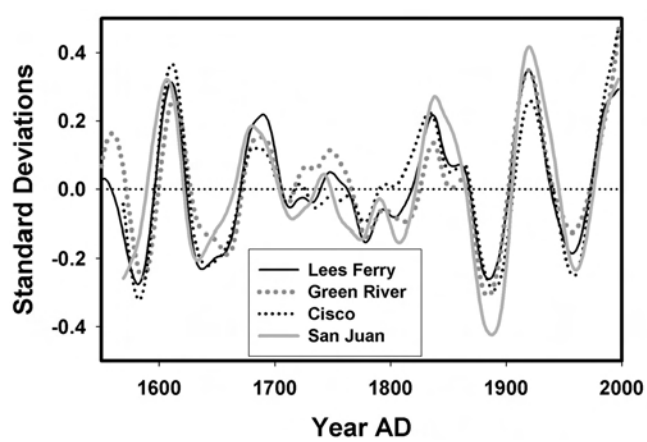


**Figure 9.** Reconstructed upper Colorado River flows, smoothed with a 50-year spline.

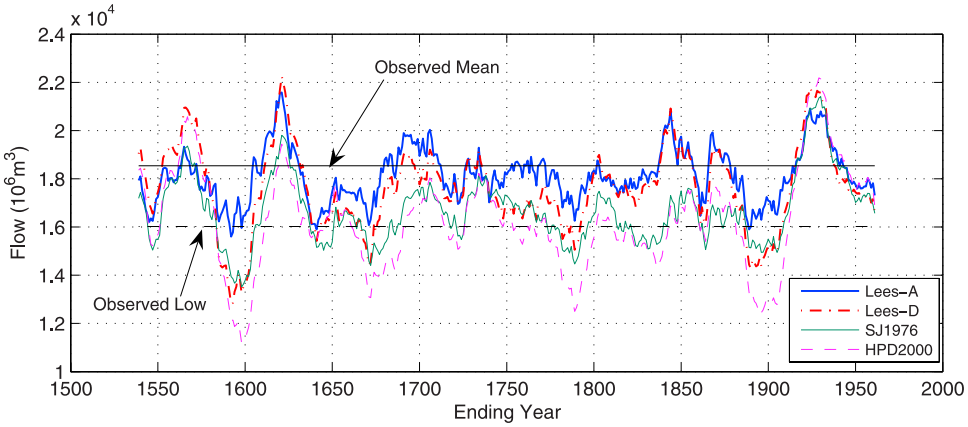


**Figure 10.** Twenty-year running means of four alternative reconstructions of the annual flow of the Colorado River at Lees Ferry for common period 1520–1961. Lees-A is our updated reconstruction from residual chronologies. Lees-D is our updated reconstruction from PCs of standard chronologies (see text). SJ1976 is the mean of two reconstructions generated by equations 2 and 3 of *Stockton and Jacoby* [1976, p. 24]. HPD2000 is the PC-based reconstruction of *Hidalgo et al.* [2000]. The horizontal lines are the 1906–2004 observed mean (solid line) and the lowest observed 20-year running mean of the 1906–2004 period (dash-dotted line).

different chronologies were used as predictors. Two of *Stockton and Jacoby*'s [1976] original sites were recollected, but it is not evident that any of the same trees were sampled. Gauge data were different as well, and both the tree ring data and gauge data in previous efforts resulted in a calibration period nearly half the length of the calibration period used in this study. Differences could also result from data processing and decisions in detrending the raw ring widths. SJ1976 and HDP2000 used standard chronologies, and models with PCs of lagged chronologies as predictors. Over the common period 1906–1961, the SJ1976 reconstruction showed a lag 1 autocorrelation of 0.36 and HDP2000 0.41, which are similar to the 0.22 and 0.31 for the models from this study that were based on standard chronologies. All of these lag 1 values are also consistent with values for the gauge record (0.25). The inclusion of lagged predictors may have the effect of enhancing the persistence in the extreme low flow years. The reliance on just seven tree ring chronologies to sample the runoff variations over the entire Upper Colorado River Basin, as with updated reconstruction Lees-A, might also present a case of potential undersampling of the watershed. However, we note that the Lees-A is closely tracked by Lees-D, a PC-based reconstruction with weights on 31 chronologies distributed over the watershed (Figure 4).

[40] We can rule out the choice of calibration period as a major source of differences among the reconstructions; recalibrating our model Lees-A on 1914–1961 (following SJ1976) instead of 1906–1995 did not appreciably affect the inferred magnitudes of past droughts. The accuracy of the naturalized flow values is clearly important to the estimated severity of reconstructed droughts: SJ1976 reported important differences in drought severity and in long-term mean reconstructed flow depending on the version of the natural flow record (several existed at that time) used to calibrate their reconstruction model.

## 5. Recent Drought (2000–2004) in a Multicentury Perspective

[41] To assess the long-term standing of the most recent drought on the Colorado River, the observed natural flows at Lees Ferry averaged over the heart of the recent drought (water years 2000–2004) can be compared with 5-year running means of the Lees Ferry reconstruction. Because of the unexplained variance in the regression however, we must allow for the possibility that the true 5-year mean for any reconstructed period may have been lower than the reconstructed 5-year mean. For this assessment, error bars were placed on the reconstructed 5-year running means.

**Table 9.** Comparative Statistics of Lees Ferry Reconstructions

| | Calibration[b] | | | Reconstruction[c] | |
|---|---|---|---|---|---|
| Model[a] | Period | $N_c$ | $R^2$ | Lowest 20-year Mean | Long-Term Mean |
| Lees-A | 1906–1995 | 7 | 0.81 | 15.6 ± 1.2 BCM (12.6 ± 0.9 MAF) | 18.1 ± 0.2 BCM (14.7 ± 0.2 MAF) |
| Lees-D | 1906–1995 | 30 | 0.77 | 12.8 ± 1.1 BCM (10.4 ± 0.9 MAF) | 17.6 ± 0.2 BCM (14.3 ± 0.2 MAF) |
| SJ1976 | 1914–1961 | 17 | 0.78[d] | 13.5 BCM (10.9 MAF) | 16.7 BCM (13.5 MAF) |
| HPD2000 | 1914–1961 | 6 | 0.82 | 11.2 ± 1.0 BCM (9.1 ± 0.8 MAF) | 16.3 ± 0.2 BCM (13.2 ± 0.2 MAF) |

[a]Reconstruction model (see text).
[b]Calibration period, number of contributing chronologies, and proportion of variance explained by regression model.
[c]Statistics of long-term reconstruction, expressed in units of billion cubic meters and million acre-feet along with 95% confidence interval estimated from the cross-validation root-mean square error (see text); statistics for common period 1520–1961.
[d]SJ1976 is a mean of two reconstructions with $R^2$ values of 0.78 and 0.87 [*Stockton and Jacoby*, 1976]; no cross-validation was performed for these models.

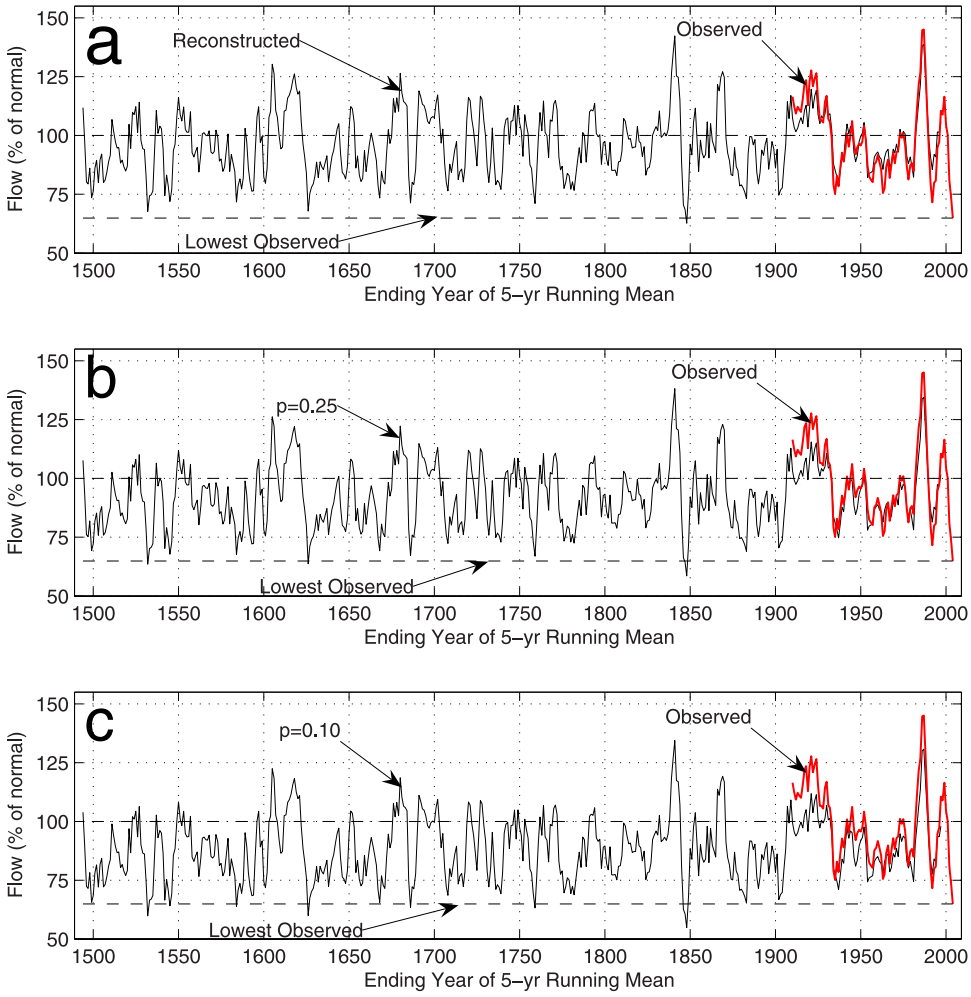


**Figure 11.** Current drought in long-term context from reconstructed 5-year running means of natural flow at Lees Ferry, Arizona. (a) Observed and reconstructed flow. (b) Observed flow and flow with 0.25 nonexceedance probability derived from reconstruction and its estimated error variance. (c) Observed flow and reconstructed flow with 0.10 nonexceedance probability. Flow is plotted as percentage of 1906–1995 mean of observed mean annual flow, or 18,788 million cubic meters (15.232 MAF). Reconstruction series is from model Lees-A (see text).

The standard error of a 5-year mean was estimated as $s_m = \mathrm{RMSE}_{cv}/\sqrt{5}$, where $\mathrm{RMSE}_{cv}$ is the cross-validation root-mean-square error of the annual reconstructed values. The computed standard error and the assumption that the errors are normally distributed yield confidence intervals and threshold levels of reconstructed 5-year mean flow with specific empirical nonexceedance probabilities.

[42] The reconstructed (Lees-A) 5-year means for Lees Ferry along with the threshold levels of flow with 0.25 and 0.10 nonexceedance probability are plotted in Figure 11 with the observed 1999–2004 mean as a baseline ("Lowest Observed") for comparison. The 5-year mean for 1999–2004 was 12,187 MCM, or 64.9% of the 1906–1995 mean natural flow. The time series plots indicate that only one 5-year period, 1844–1848, was drier than 1999–2004 (Figure 11a). Annual reconstructed flow during this period averaged 63% of normal.

[43] A probabilistic interpretation of the reconstruction indicates, however, that several other periods have a reasonably large probability of being drier than 1999–2004. Two additional periods, in the early 1500s and early 1600s, have a 25% or greater chance of being as dry as 1999–2004 (Figure 11b). Six periods in addition to the 1840s have a 10% or greater chance of being drier than 1999–2004 (Figure 11c). During the signature drought of 1844–1848, the probability is 10% that the true 5-year mean flow was as low as 54.8% of normal (10,290 MCM or 8.3422 MAF). It should be emphasized that Lees-A is the most conservative (wettest) of our Lees Ferry reconstructions, and that other versions give even more frequent past occurrences of flow lower than in 1999–2004.

## 6. Discussion and Conclusions

### 6.1. Updated Reconstructions

[44] An updated and expanded set of tree ring chronologies has enabled the generation of high-quality water year streamflow reconstructions for four key gauges in the Upper Colorado River basin; the Green River at Green River, UT; Colorado River near Cisco; San Juan near

Bluff; and the full Upper Colorado River at Lees Ferry (available online at http://www.ncdc.noaa.gov/paleo/pubs/woodhouse2006/woodhouse2006.html). These reconstructions span the common years 1569 to 1997, and account for more than 70% of the variance in the gauge records. On the basis of the extensive sensitivity analyses, differences in predictor pools and data reduction methods had little significant impact on important features (e.g., long-term mean, runs of drought years, etc.) of the reconstructions. The use of standard versus prewhitened chronologies does have some impact on the magnitude of reconstructed high and low flows, and the standard chronology models retain a degree of low-order autocorrelation similar to that in the gauge record.

[45] The Lees Ferry reconstructions presented here differ from the efforts of *Stockton and Jacoby* [1976] and *Hidalgo et al.* [2000] in suggesting a higher long-term mean for Upper Colorado River flows, and to some degree, less extreme multiyear droughts. While the choice of predictor pools and calibration data sets may factor into these differences, statistical reconstruction methodology, particularly the treatment of autocorrelation, also contributes to reduced drought magnitude and an increased long-term mean.

[46] Spatially, the relationships between reconstructed subbasin flows are similar to those in the gauge records, except for the San Juan reconstruction, which is somewhat more highly correlated with the other gauge reconstructions over the instrumental period. This enhanced similarity is lessened over the full reconstruction period. It is possible that the higher correlation between the San Juan and other basins is due to the lack of tree ring chronologies actually located in the San Juan River basin. However, exploratory analyses using several recently generated tree ring chronologies in the San Juan basin did not change these results (C. Woodhouse, unpublished). The reconstructions also capture the contribution of subbasin flows to total Colorado River flow at Lees Ferry. The subbasin flows together account for about 96% of upper Colorado River flow and contributions from the three basins are relatively stable over the 431-year common period.

[47] As seen in the comparisons of the Lees Ferry and subbasin reconstructions, over the past four centuries severe multiyear and decadal-scale droughts in the upper Colorado River basin have tended to be widespread events. The most severe 5-, 10- and 20-year droughts recorded at Lees Ferry are always reflected in the subbasin gauges, although there are subregional differences in the magnitude of droughts. When the influence of subbasin conditions on Lees Ferry flow is examined, most periods of low flow in one subbasin coincide with low flows in the other subbasins. There are some exceptions, in particular when flow in the Green River is low and the San Juan flow is high. In most of these periods of contrasting drought conditions, Lees Ferry flows are average, but a few cases (e.g., the 1930s) suggest that drought in the Green River can have an overriding influence on flows at Lees Ferry, even when high flows prevail on the San Juan. Likewise multidecadal flow regimes tend to be strongly coherent across the basin.

[48] Again, the magnitude of these persistent high and low-flow events varies across the basin, but the timing and duration of these regimes is consistent among the reconstructions.

### 6.2. Upper Colorado River Droughts and Possible Climatic Drivers

[49] The coherency of many single and multiyear droughts across the reconstructions points to common drivers for high-frequency variations in regional hydroclimate. Spectral analysis of the Lees Ferry reconstruction (Figure 6) shows significant variability in a three to seven year band associated with the El Niño Southern Oscillation (ENSO) [*Cayan et al.*, 1999]. Similar high-frequency peaks exist in the subbasin reconstructions. Examination of gauged values and ENSO indicates a good correspondence between La Niña events and low flows on the San Juan, but the relationship is less clear in the other gauges. This agrees with *Cayan and Webb* [1992] who found that streamflow in the southwestern part of Colorado typically shares the strong southwestern United States response to ENSO (i.e., increased winter precipitation during El Niño events), while the response is much weaker at gauges north of this region, and *Hidalgo and Dracup* [2003] who reported the ENSO response is much weaker in the Colorado Headwaters and Upper Green River areas.

[50] Coherency between flows at multidecadal and longer timescales also suggests that remote forcing or region-wide circulation features influence lower-frequency variations in the Upper Colorado River. Although statistical associations have been demonstrated between North American drought and North Atlantic [*Enfield et al.*, 2001], North Pacific [*Cayan et al.*, 1998; *McCabe et al.*, 2004] and Indian Ocean [*Hoerling and Kumar*, 2003] variability, more research is needed to understand how slow changes in sea surface temperatures are tied to Upper Colorado River flow regimes.

[51] Overall, intrabasin variations in reconstructed drought magnitude, combined with spectral analyses suggesting variability over a broad range of timescales (interannual to multidecadal), indicate complex and possibly nonstationary linkages between the Upper Colorado River and regional to remote forcings. Independent proxy data for ocean variability (i.e., not from western North American tree rings) and modeling studies are needed to better examine the long-term relationships between Colorado River flows and potential climatic drivers.

### 6.3. Implications for Management

[52] The recent drought has been a wake-up call for many water management agencies throughout the Colorado River basin. This drought (2000–2004), as measured by 5-year running means of water year total flow at Lees Ferry, is a markedly severe event in the context of the tree ring reconstruction extending to 1490, and the probability is low ($p < 0.10$) that any 5-year period since 1850 has been as dry. However, the current drought is not without precedence in the tree ring record. Average reconstructed annual flow for the period 1844–1848 was lower than the observed flow for 1999–2004. In view of reconstruction error, it is helpful to evaluate tree ring reconstructions probabilistically, and such an evaluation suggests that eight periods between 1536 and 1850 had at least a 10% probability of being as dry as 1999–2004. In addition, longer duration droughts have occurred in the past. The Lees Ferry reconstruction contains one sequence each of six, eight, and eleven consecutive years with flows below the 1906–1995 average (1663–

1668, 1776–1783, and 1873–1883). Overall, these analyses demonstrate that severe, sustained droughts are a defining feature of Upper Colorado River hydroclimate. Flows in the Upper Colorado are also shown to be nonstationary over decadal and longer timescales, making short-term records inappropriate for most planning and forecast applications.

[53] Although our results differ in some respects from those of *Stockton and Jacoby* [1976], the underlying messages are the same. The long-term perspective provided by tree ring reconstructions points to looming conflict between water demand and supply in the upper Colorado River basin. This suggestion has even greater relevance today. Demands on the Colorado River over the past decades have risen to meet or exceed average water availability. Any variations or shifts in climate can have a significant impact on the system [*Harding et al.*, 1995; *Christensen et al.*, 2004]. The sensitivity of the Colorado River system became abundantly clear with the onset of the recent drought. Though the southern portion of the Upper Colorado, as well as many areas in the Lower Basin, gained a measure of drought relief in the winter of 2004–2005, major reservoirs on the Colorado River remained far below capacity in 2005. In the future, predicted climatic changes, including a shift in the ratio of snowfall to rainfall and earlier snowmelt and runoff [*Cayan et al.*, 2001; *Stewart et al.*, 2004], will likely compound the strain on water resources throughout the entire Colorado River Basin.

[54] Many such climatic changes may have already begun in the western United States [*Mote et al.*, 2005], and rising temperatures will also increase demands for irrigation and hydropower generation. Proxy reconstructions can aid in planning for these scenarios by providing insights into the range of natural variability and a means to explore extreme climatic events and persistent climatic changes that are poorly captured in observational records. Reconstructions of annual streamflow for large rivers are particularly useful in that they integrate climatic variability over large regions, provide essential data for water managers, and complement existing reconstructions of seasonal climate variability [e.g., *Cook et al.*, 2004]. In concert with information on projected future changes, information on long-term variability must guide planning for drought management and economic development in the basin if we are to adequately face the social, legal and environmental challenges that coming decades will undoubtedly present.

[55] **Acknowledgments.** S. T. Gray was funded by the U.S. Geological Survey and Wyoming Water Development Commission. D. M. Meko was funded by a grant from the Arizona Board of Regents Technology and Research Initiative Fund. C. A. Woodhouse received funding from the NOAA Office of Global Programs Climate Change Data and Detection program (grant GC02-046). We greatly appreciate the comments of Edward Cook and two anonymous reviewers. We also thank Jeff Lukas, Mark Losleben, Margot Kaye, Gary Bolton, Kurt Chowanski, Stephen Jackson, Julio Betancourt, and R.G. Eddy for field and laboratory assistance in tree ring chronology data collections and chronology development and James Prairie (USBR) for providing the estimates of natural flow for Colorado River basin gauges used in the calibrations.

## References

Cayan, D. R., and R. H. Webb (1992), El Niño/Southern Oscillation and streamflow in the western United States, in *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*, edited by H. F. Diaz and V. Markgraf, pp. 29–68, Cambridge Univ. Press, New York.

Cayan, D. R., M. D. Dettinger, H. F. Diaz, and N. E. Graham (1998), Decadal variability of precipitation over western North America, *J. Clim.*, *11*, 3148–3166.

Cayan, D. R., K. T. Redmond, and L. G. Riddle (1999), ENSO and hydrologic extremes in the western United States, *J. Clim.*, *12*, 2881–2893.

Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson (2001), Changes in the onset of spring in the western United States, *Bull. Am. Meteorol. Soc.*, *82*, 399–415.

Christensen, N. S., A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer (2004), Effects of climate change on the hydrology and water resources of the Colorado River Basin, *Clim. Change*, *62*, 337–363.

Conover, W. (1980), *Practical Nonparametric Statistics*, 2nd ed., John Wiley, Hoboken, N. J.

Cook, E. R. (1985), A time series approach to tree-ring standardization, Ph.D. dissertation, Univ. of Ariz., Tucson.

Cook, E. R., and K. Briffa (1990), A comparison of some tree-ring standardization methods, in *Methods of Dendrochronology: Applications in the Environmental Sciences*, edited by E. R. Cook and L. A. Kairiukstis, pp. 153–162, Springer, New York.

Cook, E. R., K. Briffa, S. Shiyatov, and V. Mazepa (1990), Tree-ring standardization and growth-trend estimation, in *Methods of Dendrochronology: Applications in the Environmental Sciences*, edited by E. R. Cook and L. A. Kairiukstis, pp. 104–123, Springer, New York.

Cook, E. R., C. A. Woodhouse, C. M. Eakin, D. M. Meko, and D. W. Stahle (2004), Long-term aridity changes in the western United States, *Science*, *306*, 1015–1018.

Enfield, D. B., A. M. Mestas-Nuñez, and P. J. Trimble (2001), The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S., *Geophys. Res. Lett.*, *28*, 2077–2080.

Fritts, H. C. (1976), *Tree Rings and Climate*, Elsevier, New York.

Fritts, H. C., J. Guiot, and G. A. Gordon (1990), Verification, in *Methods of Dendrochronology: Applications in the Environmental Sciences*, edited by E. R. Cook and L. A. Kairiukstis, pp. 178–185, Springer, New York.

Fulp, T. (2005), How low can it go?, *Southwest Hydrol.*, *4*, 16–17.

Goodman, P. H. (1996), NevProp software, version 3, users' manual, Univ. of Nev., Reno. (http://brain.cs.unr.edu/publications/NevPropManual.pdf)

Gray, S. T., S. T. Jackson, and J. L. Betancourt (2004), Tree-ring based reconstructions of interannual to decadal-scale precipitation variability for northeastern Utah, *J. Am. Water Resour. Assoc.*, *40*, 947–960.

Haan, C. T. (2002), *Statistical Methods in Hydrology*, 2nd ed., Iowa State Univ. Press, Ames.

Harding, B. L., T. B. Sangoyomi, and E. A. Payton (1995), Impacts of severe sustained drought in Colorado River water resources, *Water Resour. Bull.*, *316*, 815–824.

Hidalgo, H. G., and J. A. Dracup (2003), ENSO and PDO effects on hydroclimatic variability in the Upper Colorado River Basin, *J. Hydrometeorol.*, *4*, 5–23.

Hidalgo, H. G., T. C. Piechota, and J. A. Dracup (2000), Alternative principal components regression procedures for dendrohydrologic reconstructions, *Water Resour. Res.*, *36*, 3241–3249.

Hoerling, M., and A. Kumar (2003), The perfect ocean for drought, *Science*, *299*, 691–694.

Mann, M. E., and J. Lees (1996), Robust estimation of background noise and signal detection in climatic time series, *Clim. Change*, *33*, 409–445.

Mardia, K., J. Kent, and J. Bibby (1979), *Multivariate Analysis*, Elsevier, New York.

McCabe, G. J., M. A. Palecki, and J. L. Betancourt (2004), Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, *Proc. Natl. Acad. Sci. U.S.A.*, *101*, 4136–4141.

Michaelsen, J. (1987), Cross-validation in statistical climate forecast models, *J. Clim. Appl. Meteorol.*, *26*, 1589–1600.

Meko, D. M., C. W. Stockton, and W. R. Boggess (1995), The tree-ring record of severe sustained drought, *Water Resour. Bull.*, *31*, 789–801.

Mote, P. W., A. F. Hamlet, M. R. Clark, and D. P. Lettenmaier (2005), Declining mountain snowpack in western North America, *Bull. Am. Meteorol. Soc.*, *86*, 39–49.

Rencher, A. C., and F. C. Pun (1980), Inflation of $R^2$ in best subset regression, *Technometrics*, *22*, 49–53.

Snedecor, G. W., and W. G. Cochran (1989), *Statistical Methods*, 8th rev. ed., Iowa State Univ. Press, Ames.

Stahle, D. W., E. R. Cook, M. K. Cleaveland, M. D. Therrell, D. M. Meko, H. D. Grissino-Mayer, E. Watson, and B. H. Luckman (2000), Tree-ring

data document 16th century megadrought over North America, *Eos Trans. AGU*, *81*(12), 121,125.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger (2004), Changes in snowmelt runoff timing in western North America under a "business as usual" climate change scenario, *Clim. Change*, *62*, 217–232.

Stockton, C. W., and G. C. Jacoby (1976), Long-term surface-water supply and streamflow trends in the Upper Colorado River Basin, *Lake Powell Res. Proj. Bull. 18*, Natl. Sci. Found., Arlington, Va.

Stokes, M. A., and T. L. Smiley (1968), *An Introduction to Tree-Ring Dating*, Univ. of Ariz. Press, Tucson.

Swetnam, T. W., M. A. Thompson, and E. K. Sutherland (1985), *Using Dendrochronology to Measure Radial Growth of Defoliated Trees*, *Agric. Handb.*, vol. 639, For. Serv., U.S. Dep. of Agric., Washington, D. C.

Torrence, C., and G. P. Compo (1998), A practical guide to wavelet analysis, *Bull. Am. Meteorol. Soc.*, *79*, 61–78.

Weisberg, S. (1985), *Applied Linear Regression*, 2nd ed., John Wiley, Hoboken, N. J.

Wigley, T., K. Briffa, and P. D. Jones (1984), On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology, *J. Clim. Appl. Meteorol.*, *23*, 201–213.

Woodhouse, C. A. (1999), Artificial neural networks and dendroclimatic reconstructions: An example from the Front Range, Colorado, USA, *Holocene*, *9*, 521–529.

Young, R. A. (1995), Coping with a severe sustained drought on the Colorado River: Introduction and overview, *Water Resour. Bull.*, *316*, 779–788.

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**INTEGRATING IMPROVED WATER SUPPLY PREDICTIVE CAPACITY AND RESPONSE INTO LOWER COLORADO BASIN POLICY AND MANAGEMENT**

A proposed continuation of an ongoing collaborative project with US Bureau of Reclamation, titled *Enhancing Water Supply Reliability Through Improved Predictive Capacity And Response*.

**DATE: July 4, 2006**

**Project Summary:** This project further develops research partnerships and extends two prior years of work on a multi-pronged approach to preparing for and responding to variable Colorado River supply reliability in Arizona. We will: a) demonstrate potential strategies for enhanced use of climate information in Bureau of Reclamation river system modeling and river operations including use of paleoclimatology, climate forecasts and climate change predictions to improve predictive capacity/reduce system vulnerability for the Colorado River system broadly, with particular focus on the lower basin and the Central Arizona Project; b) evaluate specific management tools designed to translate improved predictive capacity into enhanced supply reliability for water users, including tools that can be used by federal and state agencies, municipalities, irrigation districts, tribes and other stakeholders; c) engage with other research groups and key stakeholders to tailor research foci, approach and findings for applications of interest to Reclamation. An additional component of our proposed research includes developing an outdoor residential demand model incorporating structural, socio-economic, climatic, and environmental regressors to improve on current forecasting methodology that uses population projections and gallons per day per capita for single family and multi family residences. This more comprehensive demand model will enable us to make systematic forecasts of residential water demand under the status quo and other climate scenarios. This information is critical for translating predictive capacity into drought preparation strategies in the municipal sector.

**Duration:** 7/1/06 – 6/30/08 (24 months)

**Principal Investigators:** Bonnie Colby, Kathy Jacobs, David Meko, Peter Troch; Department of Agricultural and Resource Economics; Arizona Water Institute; Laboratory of Tree-Ring Research; and Department of Hydrology and Water Resources, respectively. (Titles and contact information below.)

**Reclamation Funds Requested: $111,959 for YEAR ONE; $114,275 for YEAR TWO**
**Leveraged Funds: $230,483**

- **Arizona Water Resources Research Center: $ 86,700**
- **Water Sustainability Program Contributions (TRIF grant support for RAs): $57,519**
- **University of Arizona salaries, Co-PI's Colby and Meko: $29,570**
- **Indirect Cost Return, VP Research and College of Agriculture: $56,694**
- **Arizona Water Institute: Jacobs time and administrative support from UA and ASU AWI staff (not quantified)**

**See attached budget and cost sharing sheets for details.**

**Critical Water Problems Addressed and Project Benefits:** Water supply variability has been a longstanding challenge in Arizona and the Colorado River Basin, stimulating large investments in water storage and delivery infrastructure. Climate change compounds the current regional water management challenge of developing and implementing shortage criteria. Reconciling irrigation needs, increases in municipal water demand, reservoir and river recreation, environmental restoration, tribal settlements and salinity management requires use of the best available tools for understanding and addressing supply variability. Recent negotiations pave the way for innovative use of water storage facilities to bank water against extended drought and for more flexible system operations.

Within Arizona, the need for this project is driven by the Environmental Impact Statement process[1], the low priority of the Central Arizona Project (CAP) and the urgent need to plan for recharge and recovery to ensure firm municipal and tribal supplies. Surface water from the Colorado River provides close to 40% of the state's water supply. Climatic conditions are the major determinant of surface water supply and expanded predictive capacity, based on the proposed work, will have multiple benefits for water supply planning, river system management and for all water using sectors.

The tree-ring record has consistently emphasized the importance of climate variation on multi-decadal time scales to runoff in the Colorado River Basin. The proposed work will contribute to more robust water-resources management by exploring ways of improving the accuracy and spatial representativeness of tree-ring information on runoff in the Upper Colorado Basin, and of integrating tree-ring information on flow variability with short-term climate predictions and longer-term projections from climate models.

Improved climate and streamflow forecasts with different time horizons allow more effective scheduling of water deliveries in the short term and evaluation of system robustness to future change over the long term. However, improved ability to predict supply variability is not enough. That capacity must be translated into improved response to supply variability by water managers and water users. The proposed work gives the Bureau of Reclamation (USBR) and Arizona water managers and users additional tools to enhance supply reliability. In addition, we plan to continue to engage stakeholders in the research process to help support the flow of timely and applicable scientific information into decision-making processes.

Multiple publications have resulted from the first two years of our work (see Garrick and Jacobs, Garrick et al., Jacobs et al, Meko and Graybill, Pittenger) in addition to the 6 e-newsletters that have been distributed by our project to a wide range of stakeholders.

**Project Objectives**

A. **Modeling and predictive capacity.** In partnership with state and federal water managers, develop recommendations for improved use of paleoclimate data, climate forecasts (seasonal to interannual) and climate change predictions (decadal) in USBR modeling, water supply planning and river system management. The second phase of the modeling component will integrate closely with the Colorado River Hydrology workgroup based in Boulder, CO. These efforts to improve predictive capacity will involve regular collaboration with academic institutions as well as USBR personnel from both the Lower and Upper Colorado Regional Offices.

B. **Evaluate Options to Translate Enhanced Predictive Capacity Into Improved Supply Reliability.** Provide and demonstrate methodology to evaluate economic tradeoffs and distributional consequences across water use sectors and other stakeholders of options to firm supply reliability. Incorporate municipal demand models into predictive strategies.

C. **Water Management Policy, Research and Education.** Continue to develop relationships between University researchers and the modelers and water managers who are interested in using climate information; assist in developing a process for integration of new information into modeling activities over time; share the findings from phase one of our work with stakeholders and refine research questions, policy applications and opportunities for future engagement.

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[1] Development of Lower Colorado River Basin Shortage Guidelines & Coordinated Management Strategies for Lakes Powell and Mead Under Low Reservoir Conditions, hereafter referred to as "EIS process".

## Approach, Methods and Procedures

### Objective A: Modeling and Predictive Capacity, Methods and Procedures

As noted by Lettenmaier (2003), there are currently no established, practical methods for incorporating long-term climate change information into water resources management and design decisions. However, Hamlet and Lettenmaier (1999b) outline an approach for evaluating the sensitivity of water resource system management to long-term climate change, which consists of four components: a) generate future climate forcing through the use of historic (directly observed and/or reconstructed) climate records or climate prediction based on climate scenarios; b) a hydrological model to translate climate scenarios into streamflow; c) a water management model; d) a set of performance metrics for the system. Based on our evolving understanding of the needs and current practices of USBR in incorporating climate information, we will continue to test these approaches for use in the Lower Colorado. We therefore propose the following process to systematically explore new methods to incorporate climate (change) information to improve predictive capacity:

**1) Refine the research questions/methods to incorporate concerns and perspectives of decision-makers.** We will hold a workshop that is focused on reporting to stakeholders on the findings of our work to date, and determining what additional questions they would like addressed, and a second workshop to integrate the current research related to climate and water management, probably focused on the 1-3 year forecast. The first workshop will be held in Phoenix in the August – October time frame, depending on availability of key participants; the second will be held in the October – March time frame, probably in Boulder, Colorado. Both workshops will be co-sponsored by the Water Resources Research Center, Arizona Water Institute and Arizona State University and the timing will be coordinated to maximize usefulness for the EIS process.

**2) Using climate information to improve predictive capacity.**

**2.1 Observed climate records:** Regression methods and the ensemble streamflow prediction (ESP) method (Twedt et al., 1977; Day, 1985) are presently the most common operational methods of accounting for climate variability in medium to long-range water resources planning (up to one year). In ESP, historic weather records are all treated as equally likely representations of future weather, and annual time series of precipitation and temperature are used to drive a hydrological model, whose initial state is based on actual basin conditions. The resulting ensemble of streamflow curves can then be used to operate water resource system models. This method is currently being investigated and will be reported in Lindenmayer's forthcoming MS thesis.

**2.2 Reconstructed climate records:** The expanded network of tree-ring chronologies in western North America (Meko et al. 1995 Cook et al. 2004) can provide spatially resolved climatic estimates for several centuries over sub-basins of the Colorado River Basin (see also item 3 below). The traditional way of extracting the essential hydrologic content from the tree-ring data has been by direct reconstruction of streamflow for selected gages by linear regression (e.g., Meko and Graybill 1995; Meko et al. 2001; Woodhouse et al. in press). An alternative approach is to apply the tree-ring data to reconstruct spatial fields of precipitation and temperature, disaggregate those reconstructions in time as needed, and route them through a hydrologic model to observe the estimated effect on runoff and streamflow. An advantage of the second approach is that nonlinearity in the climate-runoff relationship can be more effectively dealt with by a physically-based hydrologic model than by the black-box statistical tree-ring reconstruction model. Another

advantage is that climate-change scenarios of precipitation and temperature can more readily be directly superimposed on the tree-ring reconstructions to assess possible impacts on water resources of extreme climatic variations exacerbated by climate change. As part of the proposed work we will explore procedures for linking the tree-ring data to hydrologic models for the Colorado River Basin. One of the models to be explored is the VIC (Variable Infiltration Capacity) model, but other more lumped (spatially and temporally) models will also be considered. The proposed research will include interaction with BOR scientists in selecting an implementing appropriate disaggregation schemes for interfacing tree-ring data with the hydrologic models.

**2.3 Climate prediction based on known teleconnections:** Climate information can also be included by compositing the past weather records based on climatic indicators that are correlated with streamflow in the basin. For example, if a basin's streamflow shows significant anomalies during positive El Nino Southern Oscillation (ENSO) events, and a positive ENSO event is predicted for the coming year, only weather traces from years with positive ENSO events would be used. This approach has been demonstrated successfully in the context of managing the Columbia River (Hamlet and Lettenmaier, 1999a) and Folsom Reservoir in California (Yao and Georgakakos, 2001), and other locations in the U.S. (Georgakakos et al., 1998).

**2.4 Modeling climate change based on scenarios:** Our team has already demonstrated the ability to input ensemble streamflow information into the Reclamation 24 month model. As climate models continue to improve their forecast skill, further exploration of the direct use of climate model forecasts based on sea surface temperatures is worth pursuing, as is the climate change information that is available from downscaled long-term global circulation model output. The team will identify opportunities and obstacles for using climate change scenarios to generate streamflow traces for direct incorporation into river systems modeling and policy analysis.

**3) Coordinate basin-scale tree ring studies aimed at record-length extension.** Updated tree-ring reconstructions of streamflow for the Colorado River Basin emphasize the importance of site distribution and modeling choices to the final estimated drought parameters (Woodhouse et al., in press). Ongoing studies with funding from the California Department of Water Resources (Meko 2005) and U.S. Geological Survey (Connie Woodhouse, personal communication) are aimed at a small set of new field collections of remnant wood (e.g., dead snags) to lengthen the tree-ring record and sample depth of tree-ring chronologies in selected parts of the Colorado River Basin before A.D. 1300. As part of the proposed work, we will coordinate with tree-ring researchers in the Upper Colorado River Basin (UCRB) to jointly exploit these new collections for a longer-term (pre-1300 view) of variability of Colorado River flows, if possible with sub-basin resolution. The proposed workshops will serve a venue for the interaction of the tree-ring researchers.

**4) Develop recommendations and tools for improved use of paleoclimatic data, climate forecasts and climate predictions.** After assessing the quality of tree-ring reconstructions of streamflow available for input into USBR models, we will interact with USBR engineers to select the optimal form of the tree-ring reconstructions for use in river models (e.g., annual reconstructed flows, probability ranges for flows). We will examine and assess multiple avenues for including more climate prediction information in current water resources operation and planning decisions, and make recommendations on particular approaches. These range from the improved use of ESP techniques, to the direct use of downscaled and bias-corrected climate predictions and scenarios in hydrological models and water systems models, to improved ways to interpret existing model output.

**Objective B: Evaluate Options to Translate Enhanced Predictive Capacity into Improved Supply Reliability.**

**1) Develop and Demonstrate Methodology to Evaluate Economic and Distributional Tradeoffs of Supply Reliability Options**

State, federal, tribal and local policymakers are considering various tools to address supply reliability, including further interstate and intrastate water banking options and changes in mainstem and tributary reservoir management. The ongoing multi-party dialogue on shortage sharing and river operations and the EIS process will be greatly enhanced by systematic incorporation of the economic implications of climate change into evaluation of alternatives.

We will develop and demonstrate a methodology to evaluate the economic tradeoffs across water using sectors and stakeholder groups of options to firm up supply reliability. This methodology will be transferable for use by interested parties and will be constructed to facilitate systematic economic evaluation of varying scales of proposals, from revised operation of large reservoirs to changes in on-farm water management.

**2) Evaluation and Support for Reservoir Water Banking Design and Implementation**

Recent negotiations and agreements among the seven basin states regarding "Intentionally Created Surplus" (ICS) and Coordinated Operation of Lakes Powell and Mead create new possibilities for optimizing regional supply reliability using climate science. The proposals raise a host of questions about tradeoffs in allocating risks and costs, pricing water storage and exchanges involving ICS, as well as flood control and hydropower implications. Careful consideration of economic tradeoffs and coordination between reservoir banking and underground storage also is needed. We propose to examine economic components of these tradeoffs, with specific priorities determined by stakeholder engagement and the unfolding EIS process.

**3) Evaluation and Support for Forbearance Program Design and Implementation**

Forbearance programs remain a key option in adapting to supply variability linked to climate change, as well as a key component of ongoing policy discussions and the EIS process.

**3.1 Price Negotiations:** There are a number of methods for negotiating the price irrigators receive and utilizing information on-farm profitability and net returns. We propose developing guidelines for price negotiations that identify and summarize various tools for determining price, highlight the pros and cons of each, and suggest criteria for determining which negotiation method is most suitable for a specific forbearance program. The guidelines will also suggest effective approaches for successfully negotiating price with growers and agricultural districts. This task further refines and applies two years of economic research on-farm profitability and net returns to water in irrigating major crops in Yuma and La Paz Counties (Pittenger, 2006).

**3.2 Building Program Momentum:** Major impediments to development of active forbearance programs include lack of momentum and conflicts over potential program impacts. One approach to building momentum is to offer early response bonuses to farmers who sign up early to lease water. Concerns over concentration of lease payments among just a few growers (and resulting divisiveness) can be addressed in the structure of the leasing program.

**3.3 Supply Reliability and Forbearance Programs Guide:** In public outreach and stakeholder involvement, it is useful to look at examples of where irrigation forbearance programs have been implemented and to identify the specific characteristics that facilitated a program's success and the ways that prior programs have addressed difficulties. We propose the creation of a guide (either booklet or web-based) summarizing tested strategies from forbearance programs worldwide. Each brief

case overview will include information on the agricultural districts and irrigators involved in the program, the nature of the program (i.e. temporary, long-term, or permanent), criterion for inclusion in the program, how the price was negotiated, the volume of water transferred and at what price, and unique strategies utilized in structuring or carrying out the program. Such a guidebook would not only be useful to the BOR in structuring programs, but will also be useful to irrigators and irrigation districts. Information about forbearance programs that addressed urban and environmental reliability needs while also addressing the concerns of irrigators, agricultural districts, and rural communities can help build local acceptance of programs in the Lower Colorado River Basin.

**Objective C: Water Management Policy, Research and Outreach**

**1) Arizona Stakeholder Workshop.** Through interactions with the multiple stakeholders in Arizona (the Salt River Project, the Central Arizona Project, the Arizona Water Banking Authority, municipal water providers, etc) and the Reclamation offices in Phoenix and Boulder City, Nevada, the project team will develop the concept for and hold a workshop in Phoenix focused on sharing the findings of phase 1 of our project and further refining stakeholder questions relative to the enhanced use of climate information for water management. The workshop will be jointly organized and sponsored by the Arizona WRRC, Arizona Water Institute and Arizona State University.

**2) State of Research Workshop.** This workshop will include researchers from the University of Washington, the University of Colorado, Colorado State University, the University of Arizona, Arizona State University and other participants focused on evaluating the state of research in connecting climate information to critical water management issues on the Colorado and other western rivers. A likely focus will be an evaluation of current research related to climate and water management, probably focused on the 1-3 year forecast.

**3) Shortage EIS and Stakeholder Decision Support.** Collaborate with Bureau of Reclamation Lower and Upper Colorado River Offices to support integration of climate change considerations into EIS process. As needed, supply Reclamation material with analysis on water supply impacts of climate variability.

**4) Project updates.** Updates will be provided every 4 months through an email newsletter to participants.

**5) Findings from the economics, modeling and paleo-climate components.** Our findings will be shared and reviewed with Reclamation staff coordinators prior to dissemination to other project participants, to ensure accuracy of the findings.

**6) Project management and integration.** The water management and policy team will coordinate project activities and encourage interdisciplinary integration.

**Facilities.** Facilities currently available to the PIs are adequate to support this project. No additional office or lab space is required.

**Training Potential.** Six graduate students will work on this project, under the supervision of faculty PIs, for two years. (Two are fully funded under UA TRIF grants).

**Information Transfer.** Outreach and education will center on the water managers that are most closely affected by water supplies from the Colorado. However, the approach taken in this study will be transferable to other river basins. In addition, we intend to expand the number of faculty and agency participants who have access to our research process through the Arizona Water Institute.

**Qualifications of the Investigators:** The PIs have extensive professional experience in over a dozen western states and with multiple federal, state, tribal, municipal and agricultural stakeholders, Peter Troch also brings experience in related projects in Europe. Abbreviated resumes of the PIs on this project are attached.

**Interaction with Bureau and University Water Centers:** The proposed work complements the river management challenges and policy processes that Reclamation is engaged in for the Lower Colorado Region. It also complements the missions of the Arizona Water Resource Research Center (WRRC), the Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) and the Arizona Water Institute. The mission of the WRRC is to provide statewide outreach and education focused on critical water issues affecting Arizona and to provide expertise on state and regional water management and policy. This proposal focuses squarely on one of the most crucial sets of water issues facing the state, the reliability of the Colorado River supplies for the future. In addition, the majority of the region's major municipal water interests will be engaged through this project. The mission of SAHRA is to provide sustainable management of water resources in semi-arid regions. Incorporating the best available scientific information about climate and water management options into the management and operations of the Colorado River will enhance the region's ability to move towards a more sustainable system in the context of climate variability and change. The gravity component of this work is directly supported by SAHRA. The Arizona Water Institute is a consortium of Arizona's universities focused on sustainability through research, technical assistance, education and technology transfer. AWI will coordinate with the WRRC and Arizona State University on stakeholder engagement and the 2 workshops and assist with project management.

The PI's represent three different University of Arizona departments plus the Arizona Water Institute; they are active collaborators with the WRRC, SAHRA, Climate Assessment for the Southwest (CLIMAS) at the Institute for the Study of the Planet Earth, Arizona State University and Northern Arizona University. All four PIs have worked on interdisciplinary projects in the past that are focused on "real world" applications.

**Contact information for PIs:**

Colby is Professor, Department of Agricultural and Resource Economics with joint appointment in Hydrology and Water Resources, bcolby@ag.arizona.edu, (520) 621-4775.
Jacobs is Executive Director of the Arizona Water Institute and retains her affiliation as Professor in the Soil, Water and Environmental Science Department and as Deputy Director of SAHRA. kjacobs@azwaterinstitute.org (520) 626-5627.
Meko is Associate Research Professor, Laboratory of Tree-Ring Research, (520) 621-3457, dmeko@LTRR.arizona.edu.
Troch is Professor, Department of Hydrology and Water Resources, (520) 626 1277, patroch@hwr.arizona.edu

**References Cited**

Cook E. R., Woodhouse C., Eakin C. M., Meko D. M. and Stahle D. W. (2004) Long-term aridity changes in the western United States. *Science* **306**, 1015-1018.

Day, G. N. (1985) Extended Streamflow Forecasting using NWSRFS, *ASCE J. Water Resources, Planning and Mgmt*. 111(2), 157-170.

Garrick, D. and K. L. Jacobs (2006) Water Management on the Colorado River: From Surplus to Shortage in Five Years, *Southwest Hydrology*.

Garrick, D., K. L. Jacobs and G.M. Garfin (submitted), Decision Making under Uncertainty: Shortage, Stakeholders and Modeling in the Colorado River Basin, *Journal of the American Water Resources Association.*.

Georgakakos, K.P., A.P. Georgakakos and N.E. Graham (1998) Assessment of benefits of Climate Forecasts for Reservoir Management in the GCIP Region. *GEWEX News,* August, 1998, pp. 5-7.

Hamlet, A.F. and D.P. Lettenmaier (1999a) Columbia River streamflow forecasting based on ENSO and PDO climate signals, *J. of Water Res. Planning and Mgmt.*, 125, 333-341, 1999a.

Hamlet, A.F. and D.P. Lettenmaier (1999b) Effects of climate change on hydrology and water resources objectives in the Columbia River basin, *Water Resources Bulletin*, 35, 1597-1623.

Jacobs, K., B. Colby, D. Meko, and B. Nijjsen, 2005, Enhanced Water Supply Reliability Through Improved Predictive Capacity and Response, American Geophysical Union Fall Meeting, December 7, 2005. San Francisco.

Lettenmaier, D.P. (2003) The role of climate in water resources planning and management, *Water: Science, Policy and Management, Water Resources Monograph 16*, American Geophysical Union. Washington, DC, 247-266.

Meko D. M. (2005) "Drought on the Colorado River: Tree-ring Perspective, A.D. 1200s to Present." PI: D. Meko. Research grant from the California Department of Water Resources, 2005-2006.

Meko D. M. and Graybill D. A. (1995) Tree-ring reconstruction of Upper Gila River discharge. *Water Resources Bulletin* **31**(4), 605-616.

Meko D. M., Therrell M. D., Baisan C. H. and Hughes M. K. (2001) Sacramento River flow reconstructed to A.D. 869 from tree rings. *J. of the American Water Resources Association* **37**(4), 1029-1040.

Pittenger, K. Economic Value of Water in Colorado River Agriculture and in Leasing Transactions, MS Thesis, Department of Agricultural and Resource Economics, University of Arizona, in progress, 2006.

Twedt, T.M., Schaake, J.C., Jr. and E.L. Peck, (1977) National Weather Service Extended Streamflow Prediction, *Proc. Western Snow Conf.*, Albuquerque, New Mexico, 9 Pages, April.

Woodhouse C. A., Gray S. T. and Meko D. M. (2006) Updated streamflow reconstructions for the Upper Colorado River Basin. *Water Resources Research.*

Yao, H, and A. Georgakakos (2001) Assessment of Folsom Lake response to historical and potential future climate scenarios 2. Reservoir management, *Journal of Hydrology*, 249, 176-196.

## Project Components funded by Water Sustainability Program Grants

**Project Title: Estimating Arizona's Water Reserves from Space-borne Gravity Observations**, Peter Troch, PI, Awarded by WSP: $32,825, matching funds from SAHRA $17,159

This project component adds to our understanding of the amount of groundwater and surface water available in Arizona. This is a critical component of drought preparedness. Understanding changes in storage in the groundwater system seasonally and from year to year is an important aspect of water management, but today no one knows how groundwater supplies fluctuate over time. Addressing changes in groundwater storage at a broad scale is now possible thanks to technological progress in observing Earth's natural resources from space. In March 2002, NASA and DLR launched the Gravity Recovery and Climate Experiment (GRACE) twin satellites to observe, with unprecedented accuracy, monthly changes in the Earth's gravity field. Over land, one can adjust the signal for all known processes that affect gravity, producing a signal closely related to changes in total water storage. Most of Arizona's surface waters drain to the Lower Colorado River basin, which has a drainage area of about 136,000 mi2 (352,240 km2). NASA has estimated that for this size of river basins the accuracy with which GRACE can recover total water storage change is less than 1 cm of water depth. Therefore GRACE offers tremendous opportunities for progress in regional water resources management by providing means to improve the estimation of water balance terms, e.g. monthly storage changes, evapotranspiration, and basin recharge and discharge. Such progress is urgently required in order to support Arizona's management strategies of its water reserves.

This research will make significant contributions to our capacity to estimate total water storage dynamics across the state of Arizona, which directly relates to water management and drought preparedness. The predicted life time of GRACE is 8-10 years, so the expected outcome of the project is a prognostic tool for water storage change across Arizona up to 2010. Possibilities of merging different information sources on Arizona's water resources (such as large-scale hydrologic models) through advanced data assimilation procedures can be explored in a follow-up 1-year project. Particularly meriting future attention is the possibility of improving seasonal prediction of available (surface and subsurface) water.

**Project Title: Modeling outdoor residential water use,** Bonnie Colby, PI
Awarded by WSP **:** $40,111 **: Pledged by** Pima County $5,000.

Outdoor water consumption is a large segment of total residential water demand, accounting for around 40% of total annual demand and around 60% of summer demand. It is also the segment of residential demand most responsive to policy instruments. This component of our study will examine the housing structure, socio-economic, climatic, and environmental drivers of outdoor water demand using assessor and parcel, Census, temperature and precipitation, water meter readings, and remote sensing data. Significantly, we will not only investigate how housing structure and demographics shape demand but also how the heterogeneity of nearby non-residential vegetation: undeveloped lots, riparian corridors, golf courses, and parks; and the extent of native vegetation at the lot level, impacts homeowners' and tenants' decisions to water.

We will develop an outdoor residential demand model incorporating structural, socio-economic, climatic, and environmental regressors. This model will be an improvement on current forecasting methodology that uses population projections and gallons per day per capita for single family and

multi family residences. This more comprehensive demand model will enable us to make systematic forecasts of residential water demand under the status quo and other scenarios. For example, we can predict future residential water use as a consequence of modified development and swimming pool ordinances, demographic changes, and open space and riparian conservation measures. Policy makers and water managers need such empirically gathered data and improved demand forecasting methodology to make more informed water management policy. This information can be connected to the climate – based forecasts of water availability on the Colorado, and related to specific impacts on CAP deliveries and local drought planning activities.

## CV'S PRINCIPAL INVESTIGATORS

**BONNIE G. COLBY**
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**Primary Areas of Professional Experience**

Economics of Environmental Policy and Natural Resource Management
Valuation of Public Goods and Environmental Amenities
Water Resource Economics
Economics of Environmental Negotiations and Conflict Resolution

**Education**

B.S., Agricultural Economics, University of California, Davis, 1978.
M.S., Agricultural Economics, University of Wisconsin-Madison, 1981
Ph.D., Agricultural Economics, University of Wisconsin-Madison, 1983.

**Awards and Recognitions**

Mortar Board Society Citation Award for distinguished academic accomplishments in one's field, 2003.
University of Arizona Provost's Author Support Fund Award, 2002.
Faculty, Kennedy School of Government, Executive Training Program in Environmental Economics, Harvard University, 2000-01.
Governor's Water Commission, Technical Team, State of Arizona, 2000-01.
National Research Council, Committee on Upper Mississippi River Economic Analysis, 2000-02.
Sabbatical Travel Award, Hillman Foundation, 1999, New Zealand
President's Council on Sustainable Development, Western Regional Team on Natural Resources, 1994-96
National Research Council, Glen Canyon Environmental Studies Review Committee, 1991-1995
Lead economist. The National Academy of Sciences, Glen Canyon Environmental Studies Committee, 1991-1995.
Outstanding Research Scientist Award, The University of Arizona College of Agriculture, 1990
National Research Council, Committee on Western Water Management, 1989-1993
Western Agricultural Economics Association, Best Published Research Award, 1987

**Professional Appointments**

1983 - present Professor, Department of Agricultural Economics, The University of Arizona. Teaching and research in natural resource economics. Joint Appointment, Professor, Hydrology and Water Resources
1978 - 1983 Research and Teaching Assistant, Department of Agricultural Economics, University of Wisconsin.
1977 - 1978 Policy Analyst, Directors Office, California Dept. of Food and Agriculture. Economic analysis of land and water policy issues.

**Selected Research Grants and Projects**

"Water Management Innovations: 25 Years of Tribal Water Settlements", NSF Science and Technology Center, Semi-Arid Regions, 2005-06.
"Enhancing Water Supply Reliability Through Improved Predictive Capacity And Response," Co-PI on grant jointly funded by Reclamation and Water Sustainability Program, 2004-2006.
"Economic Strategies to Address Climate-related Water Supply Variability", Co-principal investigator on grant from National Atmospheric and Oceanic Administration, 2002-2006.

Evaluating the Economic and Environmental Effects of Alternative Dispute Resolution Processes, grant from Hewlett Foundation and U.S. Environmental Protection Agency, 2003-2005.

"Measuring the Economic Value of Desert Riparian Habitat, grant from NSF Science and Technology Center, Semi-Arid Regions, 2002-03.

"New Approaches to Resolving Water Conflicts," grant from NSF Science and Technology Center, 2000-02.

"Coping With Severe, Sustained Drought in the Southwestern U.S.", Multi-state project supported by U.S. Geological Survey and U.S. Army Corps of Engineers, 1992-1994.

"Dry Year Option Contracts as a Drought-Response Mechanism", U.S. Army Corps of Engineers Research Grant, 1991-1993.

**Books**

Thorson, J., S. Britton and B. Colby, *Tribal Water Conflicts: Essays in Law, Economics and Policy*, University of Arizona Press, forthcoming, 2006.

Colby, B.G. and Kathy Jacobs, *Water Policy for Urbanizing Arid Regions*, Resources for the Future Press, forthcoming, 2006.

Colby, B.G., John Thorson and Sarah Britton. *Negotiations Over Tribal Water Rights*. University of Arizona Press, 2005.

Colby, B. G., and T. P. d'Estrée, *Braving the Currents: Resolving Conflicts Over the Rivers of the American West*, Kluwer Academic Publishers, 2004.

Checchio, Elizabeth and Bonnie Colby. *Indian Water Rights: Negotiating The Future.* The University of Arizona, Tucson, 1993.

**Selected Chapters in Books**

Colby, B.G., "Economic Characteristics of Successful Environmental Dispute Resolution Outcomes", *Evaluating Environmental and Public Policy Dispute Resolution Programs and Policies*, R. Oleary and L. Bingham, editors, Resources for the Future Press, 2003, p 301-325.

Colby, B.G. "Economics of Urban Water Demand and Supply," *Managing Urban Water Demand*, N. Buras, editor, Kluwer Academic Publishers, 2003.

Colby, B. G. "Negotiated Transactions as a Conflict Resolution Mechanism: Bargaining over Water in the American West," Chapter Six in *Markets for Water—Potential and Performance*, M. Rosegrant, A. Dinar, and W. K. Easter, editors, Kluwer Academic Publishers, 1998, p.77-94.

Colby, B. G., "Markets As a Response to Water Scarcity: Policy Challenges and Economic Implications," Chapter 11 in *Advances in the Economics of Environmental Resources*, D. Hall, editor. Greenwich, Connecticut: JAI Press, pp. 211–232, 1997, 22 pages.

National Academy Committee on Glen Canyon Dam Operations, *River Basin Management*, National Academy

**Selected Refereed Journal Articles**

Bark-Hodgins, R. and Bonnie Colby, "An Economic Assessment of the Sonoran Desert Conservation Plan", *Natural Resources Journal*, forthcoming 2006.

R. Bark-Hodgins, D.E. Osgood, B.G. Colby and G. Katz and J. Stromberg. "Do Homebuyers Care If Their Environments Are Natural?" *The Journal of Real Estate Finance and Economics*, forthcoming, 2006.

Colby, B.G. and P. Orr, "Economic Tradeoffs in Preserving Riparian Habitat", *Natural Resources Journal*, 2005.

Colby, B.G. and E. Smith-Incer, "Visitors Values of Local Economic Impacts of Riparian Habitat Preservation", *Journal of American Water Resources Assoc.*, 41:709-717, 2005.

McCann, L. and Colby, B.G "Transaction Cost Measurement Related to Environmental and Natural Resource Policies", *Ecological Economics*, 2005.

Ganderton, David Brookshire, Bonnie Colby and Mary Ewers, "Market Prices for Water in the Semi-Arid West", *Water Resources Research*, 2004.

Colby, B. G., "Cap-and-Trade Policy Challenges: A Tale of Three Markets," *Land Economics* 72: 638-658, 2000.

Colby, B. G., "Evaluating Market Transactions, Litigation and Regulation as Tools for Implementing Environmental Restoration," *Arizona Law Review* 42: 381-394, 2000.

Colby, B. G., and T. P. d'Estrée. "Economic Evaluation of Mechanisms to Resolve Water Conflicts," *International Journal of Water Resource Development* 16 (No. 2): 239-251, 2000

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Ms. Katharine L. Jacobs is the Executive Director of the Arizona Water Institute, a consortium of the three Arizona state universities focused on water-related research, education and technology transfer focused on water supply sustainability. She is also the Deputy Director of the NSF Center for Sustainability of Arid Region Hydrology and Riparian Areas at the University of Arizona, and Professor and Specialist at the Department of Soil, Water and Environmental Science and Water Resources Research Center. She has more than twenty years of experience as a water manager for the state of Arizona Department of Water Resources. Her research interests include water policy, connecting science and decision-making, stakeholder engagement, use of climate information for water management applications, design of conservation programs and drought planning. Ms. Jacobs earned her M.L.A. in environmental planning from the University of California, Berkeley. She was a co-author of the National Assessment of the Impacts of Climate Change and part of the National Assessment Synthesis Team, and has served on numerous National Research Council panels.

**EDUCATION:**

University of California, Berkeley. MLA in Environmental Planning, 1981.

Professional Project: Coastal Management Plan for Anchorage, Alaska.

Middlebury College, Middlebury, Vermont. B.A. in Biology, 1977.

Cornell University, Ithaca, New York. Junior year exchange student in Biology.

**SELECTED PRIOR EXPERIENCE:**

**Special Assistant for Policy and Planning, Arizona Department of Water Resources**, August, 2002 to October, 2003. Lead staff person for the development of the Arizona Drought Plan and worked on statewide and rural water resource issues.

**Visiting Scientist, National Oceanic and Atmospheric Administration (NOAA),** September, 2001 to July 2002. Worked with scientists and researchers to improve the effectiveness of water and climate related research and applications within NOAA.

**Director, Tucson Active Management Area, Arizona Department of Water Resources**, February, 1988, to March, 2001. Managed the groundwater rights in the greater Tucson area, overseeing and managing all aspects of the Tucson office of the Arizona Department of Water Resources; developed water management policy and regulations, including mandatory conservation requirements, the Assured Water Supply Rules, recharge and recovery activities.

**SELECTED HONORS:**

Appointed to five National Academy of Sciences Panels, 1994, 2002, 2003 and 2005 (2 panels, one as chair, one as vice-chair)
Special Achievement Award, Dept. of Water Resources, 2002
Employee of the Year, Dept. of Water Resources, 2000
Tucson Regional Water Council Community Leadership Award, 1999
Supervisor of the Year, Dept. of Water Resources, 1988

**SELECTED CURRENT ACTIVITIES:**

Recently completed a co-edited book on Arizona water policy "Water Policy: Managing Water in a Rapidly Urbanizing Arid Region" with Dr. Bonnie Colby, Resources for the Future Press. Completing an article on knowledge systems for sustainable development in water management and applications of climate science in several international contexts for the Proceedings of the National Academy of Sciences and a report comparing water management and drought planning knowledge systems in Brazil and Arizona and other related reports.

**SELECTED PUBLICATIONS:**


Garrick, D. and K. L. Jacobs, 2006, Water Management on the Colorado River: From Surplus to Shortage in Five Years, *Southwest Hydrology*, Volume 5, No.3, p 8-9.

Garrick, D., K. L. Jacobs and G.M. Garfin (in review), Decision Making under Uncertainty: Shortage, Stakeholders and Modeling in the Colorado River Basin, *Journal of the American Water Resources Association.*

Holway, J.M., and K.L. Jacobs (in press), Managing for Sustainability in Arizona, USA: Linking Climate, Water Management and Growth, in Water Resources Sustainability, L. Mays, ed., McGraw-Hill.

National Research Council, (2005), Review of the GEWEX Americas Prediction Project Science Implementation Plan, Committee Report (Chair). National Academy Press, Washington, D.C.

Jacobs, K., B.Colby, D. Meko, and B. Nijjsen, 2005, Enhanced Water Supply Reliability Through Improved Predictive Capacity and Response, American Geophysical Union Fall Meeting, December 7, 2005. San Francisco.

Jacobs, K.L., G.M. Garfin and M. Lenart, More than Just Talk: Connecting Science and Decisionmaking, *Environment*, Volume. 47, No. 9, Nov. 2005, p 6-22.

Jacobs, K.L., G. M. Garfin and B. J. Morehouse, (2005), Climate Science and Drought Planning: The Arizona Experience, *Journal of the American Water Resources Association*, Volume 41, No.2, p 437-445.

Pulwarty, R.S, K.L. Jacobs and R.M. Dole, (2005), The Hardest Working River: Drought and Critical Water Problems in the Colorado River Basin in Don Wilhite, ed., Drought and Water Crises: Science, Technology, and Management Issues, Marcel Dekker.

Jacobs, K.L. and G.M. Garfin, (2004), Arizona's Drought Planning: Focusing on Adaptation *Water Resources Impact*, AWRA, Vol 6, No. 4, p 14-17.

Jacobs, K.L. and J.M. Holway, (2004), Managing for Sustainability in an Arid Climate: Lessons Learned From 20 Years of Groundwater Management in Arizona, *Hydrogeology Journal*, Vol 12, No. 1, pp.52-65.

Jacobs, K. L., S. Luoma and K. Taylor, (2003), CALFED: An Experiment in Science and Decision-making, *Environment*, Jan/Feb, pp 30-41.

U.S. Global Change Research Program, (2000), U.S. National Assessment of the Impact of Climate Variability and Change, Water Sector Chapter, National Synthesis Team Report to Congress, Cambridge University Press.

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**PROFESSIONAL PREPARATION**

1968 - 1972 Pennsylvania State University, BS Meteorology
1972 - 1974 University of Arizona, MS Atmospheric Sciences
1975 - 1981 University of Arizona, PhD Hydrology

**APPOINTMENTS**

2004-present, Associate Research Professor, Laboratory of Tree-Ring Research (LTRR)
1994-2004, Principal Research Specialist, LTRR
1991 - 1994, Adjunct Assistant Professor, LTRR
1988 – 1991, Research Associate, LTRR
1986 - 1988, Hydrologist & Assistant Director, Dept. of Water Resources, Tohono O'odham Nation, Sells, Arizona
1981 - 1986, Research Specialist, LTRR

**MEMBERSHIP**

American Meteorological Association; Committee on Statistics, 1996-98

**American Geophysical Union**

Committee on Global Change, University of Arizona
CLIMAS

**BIOGRAPHICAL SKETCH:** Dr. Meko works on topics of tree-ring analysis applied to climatology and hydrology. The geographical focus of his work has been the western United States, but he has also conducted studies in Morocco, Tibet, and northern Canada. These studies range in scale from the continent down to the small watershed. He began his career in dendroclimatology in a study relating large-scale drought fluctuations to solar variability. More recently his projects have increasingly concerned with providing data of direct relevance to water resources planning. One of his key interests is time series analysis and the development of improved statistical methods for extraction of hydrologic information from measured tree rings.

**CURRENT GRANTS**

California Dept. of Water Resources: Drought on the Colorado River: tree-ring perspective, A.D. 1200s to present (PI Meko)
Arizona Water Sustainability Program : Enhancing water supply reliability through improved predictive capacity and response (PIs Jacobs, Colby, Meko, Nijssen)
CALFED: Dendrohydrology of Blue Oak in the Central Valley of California (PI—Meko)
NOAA: Time-dependent bias in tree-ring based reconstructions (PIs –Hughes and Meko)
Salt River Project: The Current Drought in Context: A Tree-Ring Based Evaluation of Water Supply Variability for the Salt-Verde River Basin (PIs Hirschboeck and Meko)
Manitoba Hydro: The frequency, severity and causes of extreme droughts in the Winnipeg River Basin (PIs—Meko and St. George)

**SELECTED PUBLICATIONS**


Cook E. R., Woodhouse C., Eakin C. M., **Meko** D. M. and Stahle D. W., 2004, Long-term aridity changes in the western United States. Science 306, 1015-1018.

**Meko**, D.M., 1992, Dendroclimatic evidence from the Great Plains of the United States, *in* Bradley, R.S., and Jones, P.D., eds., Climate since A.D. 1500: London, Routledge, p. 312-330.

**Meko**, D.M., 1997, Dendroclimatic reconstruction with time varying subsets of tree indices: Journal of Climate, v. 10, p. 687-696.

**Meko**, D.M., 2001, Reconstructed Sacramento River system runoff from tree rings, Report prepared for the California Department of Water Resources under Agreement No. B81923-SAP # 4600000193: Tucson, Arizona, Available from: California Department of Water Resources, P.O. Box 942836, Room 1601, Sacramento, CA 94236-0001.

**Meko** D. M. (submitted) Tree-ring inferences on water-level fluctuations of Lake Athabasca. Canadian Water Resources Journal.

**Meko**, D.M., and Baisan, C.H., 2001, Pilot study of latewood-width of confers as an indicator of variability of summer rainfall in the north American Monsoon region: International J. of Climatology, v. 21, p. 697-708.

**Meko**, D.M., Cook, E.R., Stahle, D.W., Stockton, C.W., and Hughes, M.K., 1993, Spatial patterns of tree-growth anomalies in the United States and southeastern Canada: J. of Climate, v. 6, p. 1773-1786.

**Meko**, D.M., and Graybill, D.A., 1995, Tree-ring reconstruction of Upper Gila River discharge: Water Resources Bulletin, v. 31, no. 4, p. 605-616.

**Meko**, D.M., Hughes, M.K., and Stockton, C.W., 1991, Climate change and climate variability: The paleo record, *in* Managing Water Resources in the West under Conditions of Climate Uncertainty: National Academy Press, p. 71-100.

**Meko**, D.M., and Stockton, C.W., 1984, Secular variations in streamflow in the western United States: J. of Climate and Applied Meteorology, v. 23, no. 6, p. 889-897.

**Meko**, D.M., Stockton, C.W., and Blasing, T.J., 1985, Periodicity in tree rings from the corn belt: Science, v. 229, p. 381-384.

**Meko**, D.M., Stockton, C.W., and Boggess, W.R., 1980, A tree-ring reconstruction of drought in southern California: Water Resources Bulletin, v. 16, no. 4, p. 594-600.

**Meko**, D.M., Stockton, C.W., and Boggess, W.R., 1995, The tree-ring record of severe sustained drought: Water Resources Bulletin, v. 31, no. 5, p. 789-801.

**Meko**, D.M., Therrell, M.D., Baisan, C.H., and Hughes, M.K., 2001, Sacramento River flow reconstructed to A.D. 869 from tree rings: J. of the American Water Resources Association, v. 37, no. 4, p. 1029-1040.

**Meko** D. M. and Woodhouse C. A., 2005, Tree-ring footprint of joint hydrologic drought in Sacramento and Upper Colorado River Basins, western USA. J. of Hydrology 308, 196-213.

**Meko** D. M. and Woodhouse C. A. (in review) Dendroclimatology, dendrohydrology, and water resources management. In Dendroclimatology: progress and prospects (ed M. K. Hughes, T. W. Swetnam and H. F. Diaz). Springer.

Woodhouse, C. A., Gray, S. T., and **Meko**, D. M. (in press) Updated streamflow reconstructions for the Upper Colorado River basin. Water Resources Research.

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a) Education

- Undergraduate Institution: University of Ghent (B); Major: Agricultural Engineering (with major in Constructions and Mechanical Engineering); Degree & Year: Landbouwkundig Ingenieur (Agricultural Engineer), 1985
- Undergraduate Institution: University of Ghent (B); Major: Systems Control Engineering; Degree & Year: Systems Control Engineer, 1989
- Graduate Institution: University of Ghent (B); Major: Hydrology; Degree & Year: PhD in Hydrology, 1993

b) Professional Appointments (since 1993)

November 2005 – Now: Full Professor at Department of Hydrology and Water Resources, The University of Arizona, USA

August 1999 – October 2005: Full Professor and Chair of Hydrology and Quantitative Water Management, Wageningen University, NL

January 1996 – July 1999: Associate Professor at Department of Forest and Water Management, University of Ghent, B

October 1993 – December 1995: Assistant Professor at Department of Forest and Water Management, University of Ghent, B

Publications Related to the proposed project:

**Troch**, P.A., F.P. De Troch, and W. Brutsaert, 1993. Effective Water Table Depth to Describe Initial Conditions Prior to Storm Rainfall in Humid Regions, *Water Resources Research*, 29(2), 427-434.

Hoeben, R. and P.A. **Troch**, 2000. Assimilation of active microwave observation data for soil moisture profile estimation, *Water Resour. Res.*, 36(10), 2805-2819.

**Troch**, P., N. Verhoest, P. Gineste, C. Paniconi and P. Merot, 2000. Variable source areas, soil moisture and active microwave observations at Zwalmbeek and Coët-Dan. Chapter 8 in R. Grayson and G. Blöschl (Eds.) *Spatial Patterns in Catchment Hydrology: Observations and Modelling*. Cambridge University Press, Cambridge, pp. 187-208.

Schuurmans, J.M., P.A. **Troch**, A.A. Veldhuizen, W. Bastiaanssen, M. Bierkens, 2003. Assimilating remotely sensed latent heat fluxes in a distributed hydrological model, *Advances in Water Resources*, 26(2), 151-159.

**Troch**, P.A., C. Paniconi, and E.E. van Loon, 2003. Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 1. Formulation and characteristic response. *Water Resour. Res., 39* (11), 1316, doi:10.1029/2002WR001728.

**Troch**, P.A., C. Paniconi and D. McLaughlin, 2003. Preface: Catchment-scale hydrological modeling and data assimilation, *Advances in Water Resources*, 26(2), 131-135.

Teuling, A., R. Uijlenhoet and P.A. **Troch**, 2005. On bimodality in warm season soil moisture observations, *Geophysical Research Letters*, *32*, L13402, doi:10.1029/2005GL023223.

Hasan, S., P.A. **Troch**, J. Boll and C. Kroner, 2005. Modeling the hydrological effect on local gravity at Moxa, Germany, *Journal of Hydrometeorology*, in press.

Other significant publications:

**Troch**, P.A., M. Mancini, C. Paniconi, C. and E.F. Wood, 1993. Evaluation of a Distributed Catchment Scale Water Balance Model. *Water Resources Research*, 29(6), 1805-1817.

**Troch**, P.A., J.A. Smith, E.F. Wood, and F.P. De Troch, 1994. Hydrologic Controls of Large Floods in a Small Basin: Central Appalachian Case Study, *Journal of Hydrology*, 156, 285-309.

Altese, E., O. Bolognani, M. Mancini, and P.A. **Troch**, 1996. Retrieving Soil Moisture Over Bare Soil From ERS-1 Synthetic Aperture Radar Data: Sensitivity Analysis Based on a Theoretical Surface Scattering Model and Field Data, *Water Resources Research*, 32(3), 653-661.

Verhoest, N., P.A. **Troch** and F.P. De Troch, F.P., 1997. On the applicability of Bartlett-Lewis rectangular pulses models for calculating design storms at a point, *Journal of Hydrology*, 202(1-4), 108-120.

Van Loon, E.E. and P.A. **Troch**, 2002. Tikhonov regularization as a tool for assimilating soil moisture data in distributed hydrological models, *Hydrological Processes*, 16, 531-556.

c) Professional Service

Service to the scientific and engineering community outside organization: applicant organized two international workshops on Catchment-scale Hydrological Modeling and Data Assimilation (CAHMDA) (Wageningen, 2001 and Princeton, 2004); he also chaired the National Center for Hydrological Sciences (know as the Boussinesq Center) in the Netherlands in 2005; he was member of the Foresight Study Committee on Hydrological Sciences of the Netherlands Royal Academy of Arts and Sciences (2002-2005). In Fall 2005, he co-organized an international PUB workshop on Hillslope Intercomparison Experiments (SLICE) at Blue River, Oregon. He is Troika leader of Theme 5: New Hydrological Theory within IAHS-PUB (2005-2007).

d) Collaborators & Other Affiliations

- Collaborators and co-editors: John Albertson (Duke University), Wim Bastiaanssen (Water Watch), Alexis Berne (Wageningen University), Marc Bierkens (Utrecht University), Patrick Bogaart (Wageningen University), Jan Boll (University of Idaho), Han Dolman (Free University of Amsterdam), Jim Freer (Lancaster University), Majid Hassanizadeh (Utrecht University), Francois Hupet (Universite Catholique de Louvain), Jim Kirchner (UC Berkeley), Ronald Klees (Technological University Delft), Corina Kroner (University of Jena), Emiel van Loon (University of Amsterdam), Marco Mancini (Politecnico di Milano), Jeff McDonnell (Oregon State University), Kevin McGuire (Georgia University of Technology), Dennis McLaughlin (MIT), Nicola Montaldo (Politecnico di Milano), Claudio Paniconi (CNRS, Quebec), Valentijn Pauwels (University of Ghent), Huub Savenije (Technological University Delft), Justin Sheffield (Princeton University), Murugesu Sivapalan (University of Illinois), Han Stricker (Wageningen University), Bob Su (ITC), Ryan Teuling (Wageningen University), Paul Torfs (Wageningen University), Remko Uijlenhoet (Wageningen University), Niko Verhoest (University of Ghent), Rafael Wojcik (Princeton University), Eric Wood (Princeton University), Sjoerd van der Zee (Wageningen University).
- Graduate and Postdoctoral Advisors: Francois De Troch (Professor Emeritus University of Ghent; graduate advisor), Eric Wood (Princeton University (Postdoctoral advisor)
- PhD Thesis Advisor of: Lamia Lajili (1999), Rafael Wojcik (2000), Niko Verhoest (2000), Yves van Herpe (2000), Martin Knotters (2001), Marc Hoffmann (2003), Arno Hilberts (2005), Ryan Teuling (2006), Shaakeel Hasan (2007), Ali Talebi (2008), Kaka Shahedi (2008), Hanneke Schuurmans (2008), Joost Heijkers (2008), Hidde Leijnse (2008), Tessa van Wijnen (2008), Ruud Hurkmans (2009); Total: 16

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