THE FICKLE FLOW

What Climate Reconstructions and Forecasting Tell Us About the Future of the Colorado River

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Abstract: Early settlement of the American West was predicated on settlers' ability to access water. As populations grew and demand increased, infrastructure to support water delivery kept pace, but we have reached a turning point. Water delivery is no longer limited by conveyance, but rather the reliability of its supply. The Colorado River, the primary water source for nearly 40 million people, embodies the challenges facing water managers in the West. This paper considers the historical climate in the Southwestern United States as well as climate forecasts through the end of the century and what these tell us about Colorado River flow. It outlines research methods used for reconstructing paleoclimate and provides an explanation for the uncertainty in forecasting flows based on past and future models. The paper concludes with examples of successful adaptation to water shortage and policy suggestions for decision-makers based on existing research.

INTRODUCTION

Drought has driven 21st century water management in the southwestern United States for nearly two decades. The fifteen year period from 2000 to 2014 saw a 19% decrease in the average flow of the Colorado River compared to the 1906-1999 average (Udall & Overpeck 2017). Effects of this prolonged drought were largely mitigated by the capacity of reservoirs like Lakes Mead and Powell; however, the result was a significant drop in storage. In response, the Secretary of the Interior developed "Interim Guidelines" to manage reservoir levels through 2026 using a combination of management techniques (Rajagopalan et al. 2009). With expiration of the interim plan eminent, continued periods of drought and the threat of climate change create uncertainty for future Colorado River flow volume and the ability of the system to support coming demand. Variability in flow necessitates additional actions to increase adaptability and reduce demand. There are many examples of successful management techniques in the western US and the populous has already demonstrated willingness to adjust consumption.

This paper examines the various approaches taken by researchers when considering Colorado River flow variability, including paleoclimate reconstruction from tree rings and models forecasting climate change. It outlines uncertainties inherent to forecasting flows and the importance of distinguishing the effects of temperature and precipitation independently. Following an examination of existing management techniques, options for future Colorado River management are considered, including future research and modeling needs.

BACKGROUND

Successful settlements in the early days of the American West relied on a mixture of ambition and blind faith in water security. The pioneers depended on riparian flows and expansion was limited by proximity to rivers. Following his 1869 expedition down the Colorado River, John Wesley Powell sought to institutionalize this approach, famously suggesting all development in the West should be carefully planned within the limits of basin hydrology (Reisner 1986). The lure of cheap land and an expanding agricultural society overwhelmed the reasoned overtures of Powell and others.

As western migration increased, the US government introduced the Reclamation Act of 1902, which established the Reclamation Society (later changed to U.S. Bureau of Reclamation) overseen by the Department of the Interior. The Reclamation Act authorized dams and irrigation projects to provide farms no larger than 160 acres with water at subsidized rates. Over time, variability in flows, especially in California's Imperial Valley and Mexico, led to increasing demand for more federal support and larger dams to improve reliability (Hanak et al. 2011).

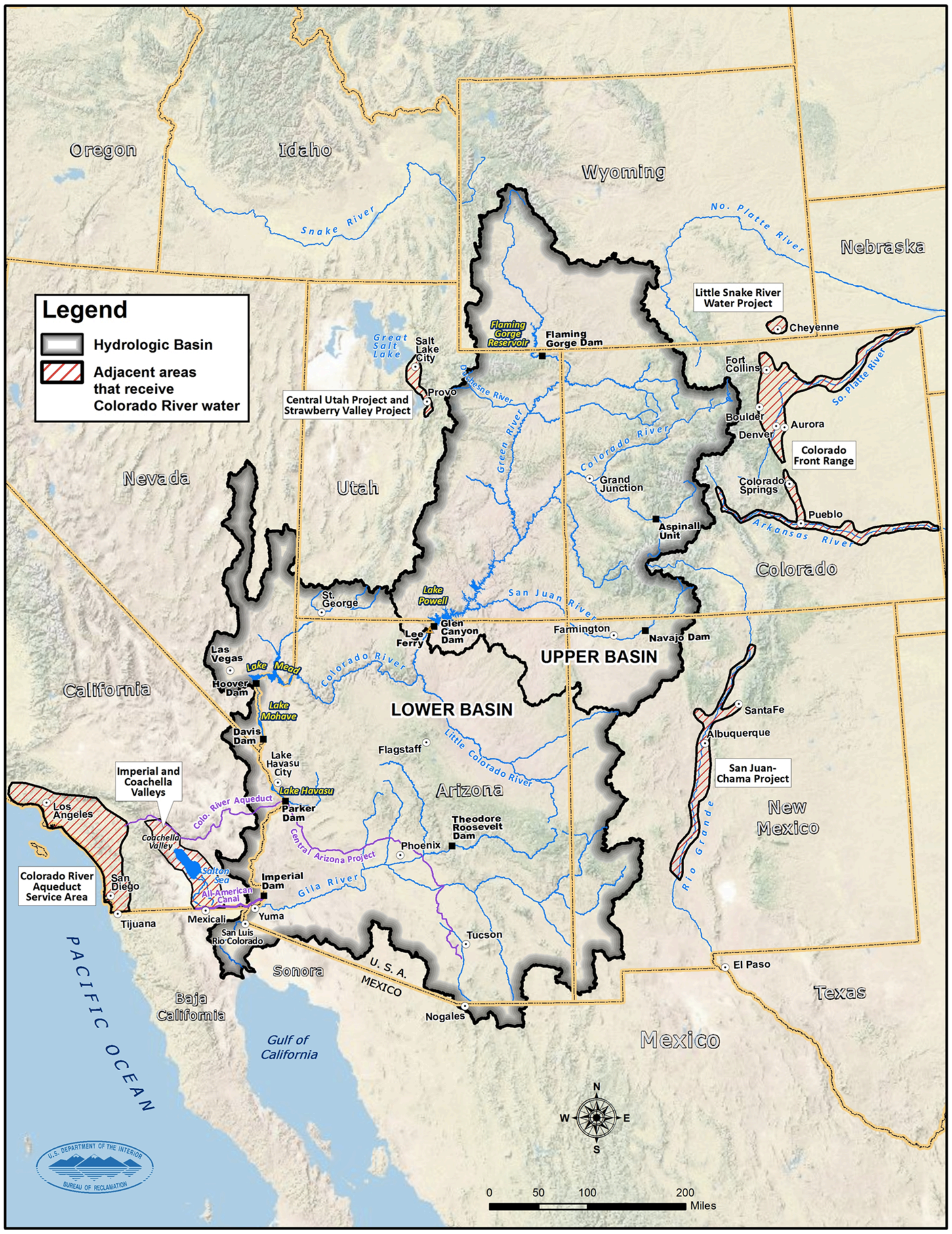

Figure 1: Colorado River Basin *[Source: US Bureau of Reclamation]*

The area critical to water delivery in the Southwest, comprising several U.S. Bureau of Reclamation (USBR) projects, is the Colorado River Basin (Figure 1). A complex system of dams, water rights allocations, and management structures governs water delivery in the region based on assumptions about flow availability. The Colorado River Compact of 1922 established annual allotments of 7.5 million acre-feet (1 MAF = 1.233 x 10^9 m^3) to Upper Basin states (Colorado, Utah, Wyoming, and New Mexico), and 7.5 MAF to Lower Basin states (California, Nevada, and Arizona) (Hanak et al. 2011). A later treaty with Mexico in 1944 allowed for 1.5 MAF to be sent across the border, resulting in 16.5 MAF of total allotted water. During initial negotiation of the compact, calculations of the available water were computed from a 20 year data set of stream gauge flow at Yuma, AZ, which experts used to establish an anticipated annual flow of 17 MAF. The river has averaged just 15.5 MAF of annual flow since formation of the compact (Fleck 2016; USBR 2012). Over allocation compounds the problems of shortage caused by drought.

Shortage in dry years has been largely mitigated by the 60 MAF of reservoir storage capacity along the river. This capacity, nearly four times the annual flow of the river, is unprecedented in other river systems (Vano et al. 2014) and 50 MAF of the storage is split between Lake Mead and Lake Powell alone (Rajagopalan 2009). Reliance on reservoirs to smooth irregular flows has led to a steady decrease in the overall combined volume of Lakes Mead and Powell since Lake Powell first filled to capacity in 1980 (Udall & Overpeck 2017; USBR 2017). According to Collum & McCann (2014), power shortage will occur 75% of the time if Lake Mead falls below 1000 feet above sea level, triggering equalization releases from Lake Powell that cause the Powell level to fall below minimum power pool. To date, Lake Mead’s lowest recorded level since fill was 1071.61 feet elevation in July of 2016 as compared to its 1229 feet elevation capacity (USBR 2018). These same Powell releases add pressure to Upper Basin states to curtail water to meet requirements for Lower Basin delivery (Udall & Overpeck 2017).

The original Colorado River Compact did not account for management of significant flow decline and its potential effects on each basin. In the context of a longer timeline of flow, decision-makers may have taken an alternate course.

PALEOCLIMATE AND MEGADROUGHT

Dendrochronology, the science of dating tree rings to establish timelines of atmospheric and environmental changes, has allowed researchers to build out a more robust understanding of early climate in the western United States, which drives reconstructions of Colorado River flow. “[T]ree 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” (Woodhouse et al. 2006, pg. 2). Reconstructed records demonstrate significant variability in the historical flow, including longer periods of drought than experienced in the 21st century (Cook et al. 2010). These multi-decadal dry periods are referred to as megadroughts. Comparison of these periods to more recent observed records provide insights for decision-makers and researchers into flow variability.

Colorado River Flow Reconstructions

In 1976, Stockton and Jacoby performed the first study of tree rings for the purpose of reconstructing annual streamflows at Lees Ferry, the location of a USGS gauge which serves as a proxy for Upper Basin natural flow (Figure 1). The record produced spanned the period from

1520 to 1961 and showed the early 20th century as the period of highest average annual flows (Woodhouse et al. 2006; Vano 2014). This exceptionally wet period corresponds to the period used for negotiating the Colorado Compact, which explains the discrepancy between the total water allocated annually and annual river flow volume. Additional reconstructions since 1976 have supported this finding.

Woodhouse et al. (2006) produced several reconstructions based on various stream gauges throughout the Upper Colorado River Basin, which demonstrate the early 20th century period of higher streamflow. The analysis included gauges from the Green River at Green River, Utah, the Colorado River near Cisco, Utah, the San Juan River near Bluff, Utah, and the Colorado River at Lees Ferry, Arizona. The multiple linear regression incorporated data from 62 available tree ring chronologies spanning the period from 1600 to 1997. By comparing USBR observed data to models generated from tree ring data, the study produced models based on the full pool of available tree ring records for each gauge and also various limited pools according to watershed boundaries. The reconstructed models accounted for 72-81% of the variance in the gauge records (Appendix A). While they demonstrated a higher long-term mean than previous reconstructions from Stockton and Jacoby and Hidalgo, the models also demonstrated more severe droughts occurred prior to the 20th or 21st centuries.

The following year, Meko et al. published a paper extending the record to A.D. 762. This study used cores collected from 11 sites in the Upper Colorado River Basin. To generate the proxy reconstruction, dimensionless indices were created as a ratio of ring width to an empirically fit growth curve. To limit potential damping of the climate signal, a minimum core length and subsample signal strength were specified. As in the Woodhouse et al. study, Meko included USBR streamflow data observed from 1906-2004 at Lees Ferry. Single-site regression modeling for each of the 11 sites accounted for anywhere from 25-57% of the flow variance. A second analysis with stepwise regression of flow accounted for more flow variance. Four different start periods were identified and as the available number of chronologies increased, so did the R^2 value, ranging from 0.60 to 0.77 (Meko et al. 2007, pg. 2) (Table 1). Comparison to the Woodhouse et al. model (2006) shows consistency for the period 1490 to 1997.

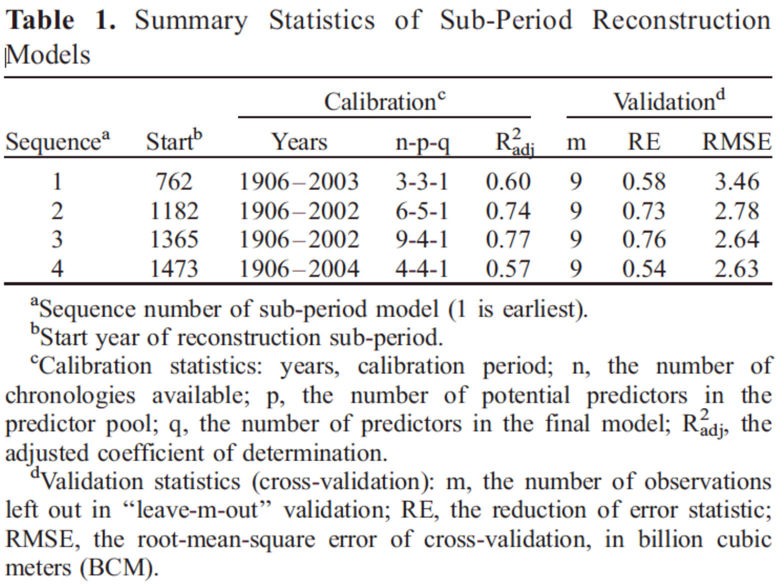

Table 1. Summary Statistics of Sub-Period Reconstruction Models

		Calibration[c]			Validation[d]		
Sequence[a]	Start[b]	Years	n-p-q	R^2_{adj}	m	RE	RMSE
1	762	1906–2003	3-3-1	0.60	9	0.58	3.46
2	1182	1906–2002	6-5-1	0.74	9	0.73	2.78
3	1365	1906–2002	9-4-1	0.77	9	0.76	2.64
4	1473	1906–2004	4-4-1	0.57	9	0.54	2.63

[a] Sequence number of sub-period model (1 is earliest).

[b] Start year of reconstruction sub-period.

[c] Calibration statistics: years, calibration period; n, the number of chronologies available; p, the number of potential predictors in the predictor pool; q, the number of predictors in the final model; R^2_{adj}, the adjusted coefficient of determination.

[d] Validation statistics (cross-validation): m, the number of observations left out in "leave-m-out" validation; RE, the reduction of error statistic; RMSE, the root-mean-square error of cross-validation, in billion cubic meters (BCM).

Source: Woodhouse et al. 2006

This drought analysis identified significant flow reductions in Medieval times (11th century). One 25 year period (A.D. 1130-1154) was marked by greater than 16% reduction in mean flow with a 10% chance the reduction was as much as 21%. This extreme drought occurred during a dry period characterized by an absence of high annual flows over six decades (A.D. 1118-1179) (Meko et al. 2007) (Figure 2).

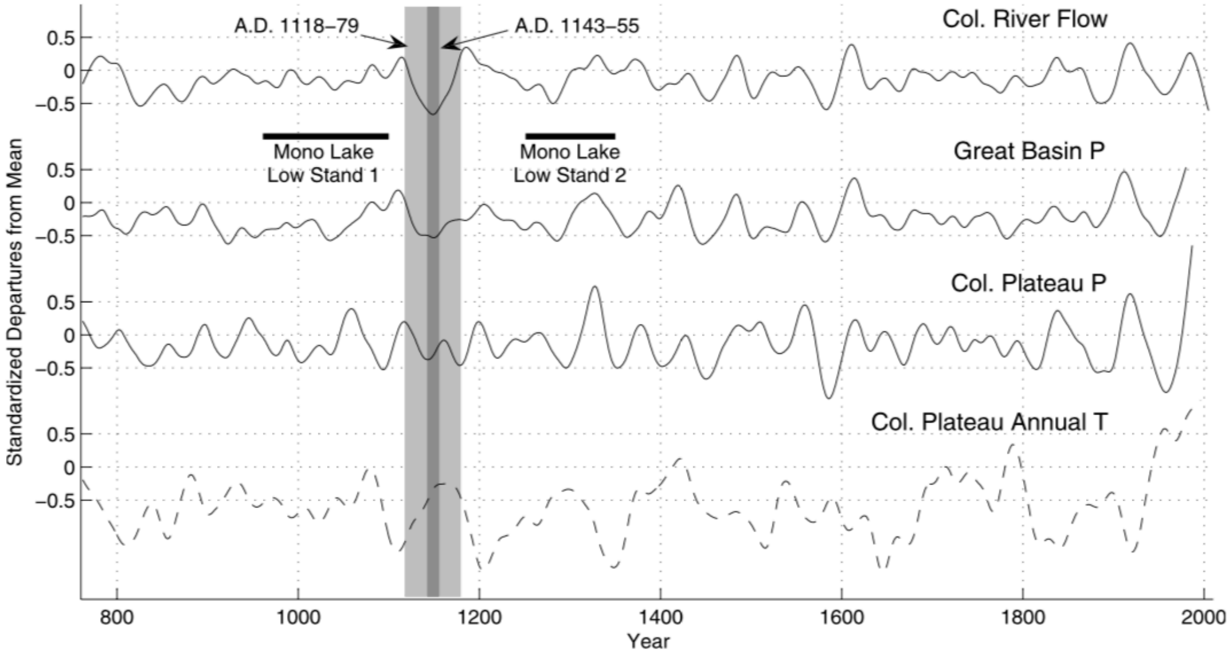

Figure 2: Medieval drought on Colorado River in regional context of other paleoclimatic reconstructions. Core and broad window for Colorado River drought shaded. Other plotted series are: Great Basin annual precipitation [Hughes and Funkhouser, 1998] (six-chronology reconstruction), Colorado Plateau October-July precipitation, and Colorado Plateau annual average maximum temperature [Salzer and Kipfmueller, 2005] All plotted series generated by converting annual reconstructions to standardized departures (using means and standard deviations for period beginning with 1906), followed by smoothing with 41-year spline to emphasize multidecadal departures. Horizontal bars at inferred Mono Lake low stands follow Stine [1994]. *[Source: Meko et al. 2007]*

A group of researchers at the University of Arizona demonstrated even earlier periods of unusual dryness and extended drought, expanding the record as far back as 268 B.C. using living and remnant bristlecone pine (*Pinus aristata*) from the headwater region of the Rio Grande River, Colorado (Routson et al. 2011). This area of Colorado serves as the headwaters for both the Colorado River and Rio Grande River and so can be compared to existing Colorado River reconstructions. The new reconstruction demonstrates a multi-century period from 1-400 A.D. of unusual dryness. Within this period, an extreme drought of almost five decades occurred in the 2nd century that corresponds to an event shown in other chronologies at Tavaputs, UT [Knight et al. 2010] and El Malpais, NM [Grissino-Mayor 1996) (Routson et al. 2011).

To better understand the sensitivity of the bristlecone pine analysis, the study considered gridded PRISM (Parameter elevation Regression on Independent Slopes Model) data of monthly precipitation and temperature spanning A.D. 1895-2009 from the Rio Grande headwaters hydrologic unit compared to tree growth for the same period. This analysis combined with a comparison to drought severity index and temperature reconstructions indicated a consistent moisture balance signal extending back 2000 years.

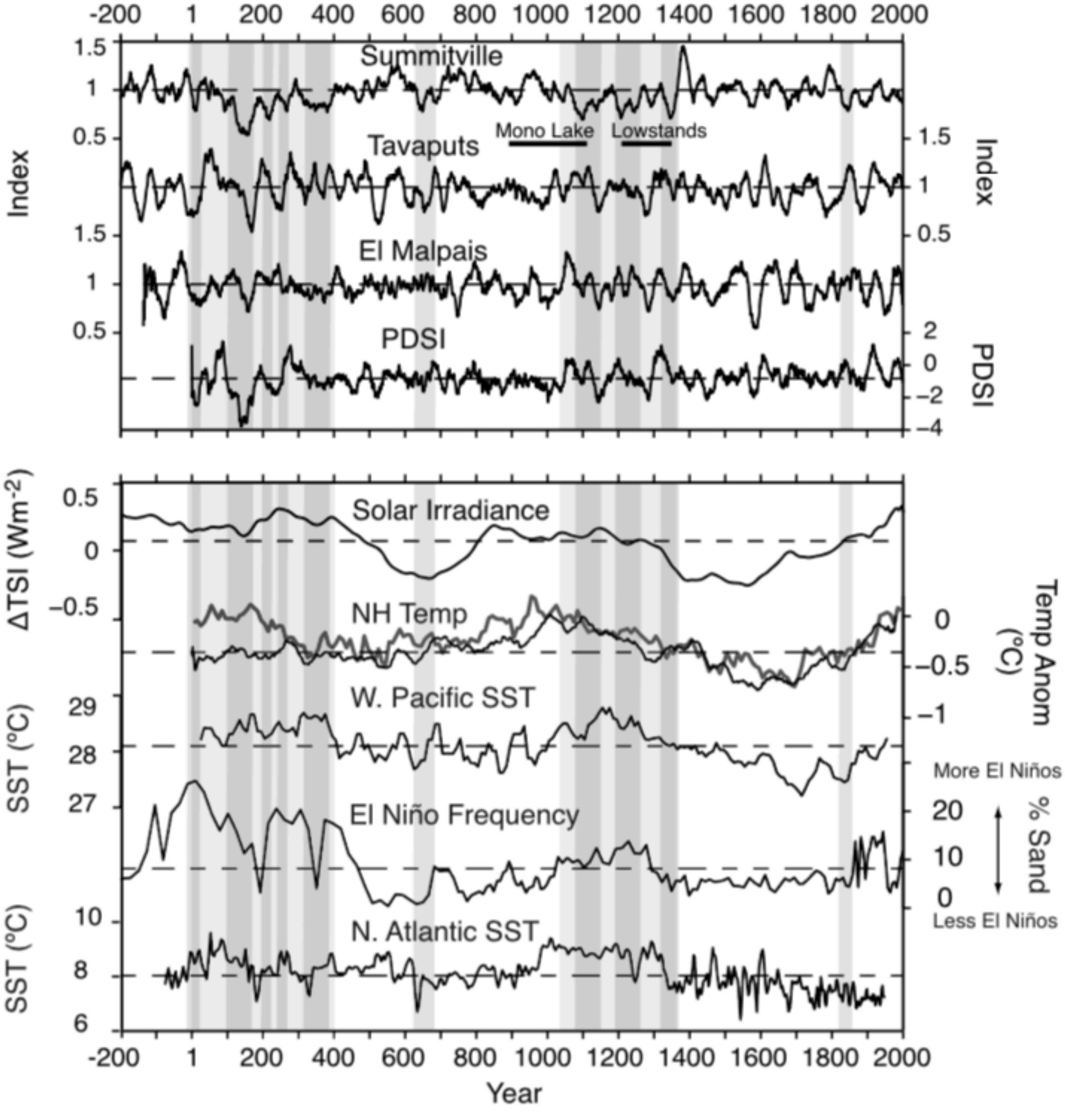

Figure 3: (top) Colorado Plateau region moisture records including Summitville CO, Tavaputs UT [Knight et al., 2010], El Malpais NM [Grissino-Mayor, 1996], PDSI [Cook et al., 2008] showing the timing and severity of the 2nd century megadrought. (bottom) Records of variables that may influence drought in the Four Corners region: inferred total solar irradiance (smoothed with a 50 yr MA) [Steinhilber et al., 2009], Northern Hemisphere temperature (smoothed with a 50 yr MA) [Moberg et al., 2005] (black) and [Ljunqvist, 2010] (grey), west Pacific warm-pool sea surface temperature [Oppo et al., 2009], El Niño frequency [Conroy et al., 2008], and Northern Iceland SST [Sicre et al., 2008]. Shaded bars are the same as in Figure 2. *[Source: Routson et al. 2011]*

Figure 3 visually demonstrates the study comparisons to oceanic and atmospheric circulations from other researchers. This begins to explore possible causes for this drought and indicates warmer temperatures may have influenced 2nd century drought in the Colorado River Basin. The study found it is also possible that large scale weather patterns, like La Niña events, had some influence on drought. Although it was unclear whether influence from Atlantic sea surface temperature had an effect for the 2nd century drought, medieval drought data indicated north Atlantic weather patterns were an influence. The similarities between the 2nd century and the later medieval period aridity suggests a likelihood that severe conditions were not an anomaly.

Uncertainty in Reconstructions

Each of the reconstructions discussed above exhibited past periods of megadrought. While varied in duration, similarities between precipitation and temperature response for recurring drought events provide possible indicators of future drought triggers. As with any model, there is an element of uncertainty in tree ring reconstructions. Meko et al. (2007) discussed the absence of climate factors in tree ring reconstructions like temperature through length of the growing season and moisture available in snowpack storage (Vano 2014). Looking to the future, an added uncertainty is climate change. There is an indication precipitation was the primary driver of past events, whereas the temperature increase of future climate change is likely to drive future drought. Recall the Colorado Compact negotiated on the basis of limited observed flow data. As anthropogenic influences generate temperatures previously unseen across the Southwest, making decisions purely on an assumption of stationarity is ill-advised (Castle 2016).

GLOBAL CLIMATE MODELS AND FORECASTING

The Intergovernmental Panel on Climate Change (IPCC) assesses the risks, possible outcomes and potential remedies for climate change. This body of scientists from around the world evaluates the available scientific literature to generate reports which summarize the findings across the spectrum of research. To date, five reports have been released. To project and plan for various climate change outcomes, the IPCC Fifth Assessment Report (IPCC AR5) bases analysis on a group of four representative scenarios, called Representative Concentration Pathways (RCPs). These scenarios are examples of possible emissions-based radiative forcing, the difference between globally absorbed and emitted radiation measured in watts per meter squared (W/m^2). Using each pathway (RCP2.6, RCP4.5, RCP6.0, and RCP8.5), existing global climate models are run to predict outcomes for the end of the century, A.D. 2100 (Markovich 2017).

Key Forecasting Considerations

The IPCC AR4 demonstrated the effects of different models. Of the 112 models run in the report for future climate projections, one third indicated either no change or an increase in Colorado River flow. The other two thirds indicated a decrease (Vano 2014). This variability can be largely attributed to two key considerations: temperature and precipitation.

Temperature

While varying degrees of warming are predicted, researchers agree future temperature increase will be an outcome of climate change. This has been verified using additional methods beyond tree rings, ice cores, and radiative forcing predictions. In Huang, Pollack & Shen's borehole study published in *Nature* (as referenced in Overpeck 2000), the authors evaluated temperature readings from 616 boreholes on six continents. Accounting for heat conduction from below (Earth's interior) and above (the atmosphere), the study demonstrated a trend for increasing temperature.

Increasing temperature has various implications for Colorado River flow. The river is fed by snowpack accumulation in the Rockies. As temperatures increase, snowpack is reduced and with it, late-season snowmelt (Overpeck & Udall 2010). Changing timing of the hydrograph for the river adds complexity to dam operations as reservoir storage does not benefit from spring melt streamflow.

Udall & Overpeck (2017) perform an analysis of temperature increases based on historical streamflow reductions. Considering the 2000-2014 drought in the southwest, they identify average flow as 19.3% below the 1906-1999 mean. Their study uses this flow loss as a basis for analyzing future streamflow reductions based on temperature sensitivity, the percent change in flow per degree change in temperature. The value used is in the study is -6.5% / ºC from Vano et al. (2012). Using this value in conjunction with Coupled Model Intercomparison Project 3 and 5 data (CMIP3 and CMIP5) for temperature increases, Udall & Overpeck establish a mean flow loss ranging from -8% by mid-century on the low end to as much as -55% by end of century (Appendix B). The analysis also indicates the calculated amount of precipitation that would be required to offset the corresponding temperature-induced streamflow loss.

Precipitation

Model resolution factors into precipitation scenario outcomes. Using a McCabe and Wolock model and parameters, Vano et al. showed a dependence between predicted runoff, temperature sensitivity (Δ flow % per ºC), and grid spacing (2014). As grid spacing increased, predicted runoff and temperature sensitivity decreased. This section began with a discussion of the discrepancies between model predictions. Vano et al. compared several models and suggest simulations of land processes, atmospheric process, and land surface combined with varying statistical downscaling methods lead to the variety of outcomes.

Understanding Forecasts

Conceptualizing percentage decrease in streamflow or the relative global mean temperature increase is challenging. Presenting the information in an alternative narrative can be helpful. The risk of water storage failure is one metric for understanding the severity of projections. Rajagopalan analyzed the possible changes to water availability due to climate variability and what options exist to mitigate these changes (2009). The study established a probability of storage going dry based on existing management assumptions of demand growth, historical climate variability, and projected reductions in flow due to climate change.

The analysis relied on a simple water balance where storage equaled inflow minus outflow using data from the Department of Interior for Lees Ferry flows as well as paleoreconstructed streamflow. Through stochastic methods using both data sets, the researchers established a model streamflow variability. The Laws of the River were then applied based on existing regulations, especially the 'Interim Guidelines' introduced at the beginning of this paper. The study modeled climate change as a linear change in flow up to either a 10% (CC10) or 20% (CC20) reduction as of A.D. 2057.

Based on current management methods, the study found the system to be resilient through 2026, which corresponds to the end of the ‘Interim Guidelines’. After 2026, probabilities of reservoir depletion varied from 26% (CC10) to 51% (CC20) by 2057 (Figure 4). The authors noted a change in demand of 6% yields a probability decrease of 33%, which implies a significant opportunity for mitigation.

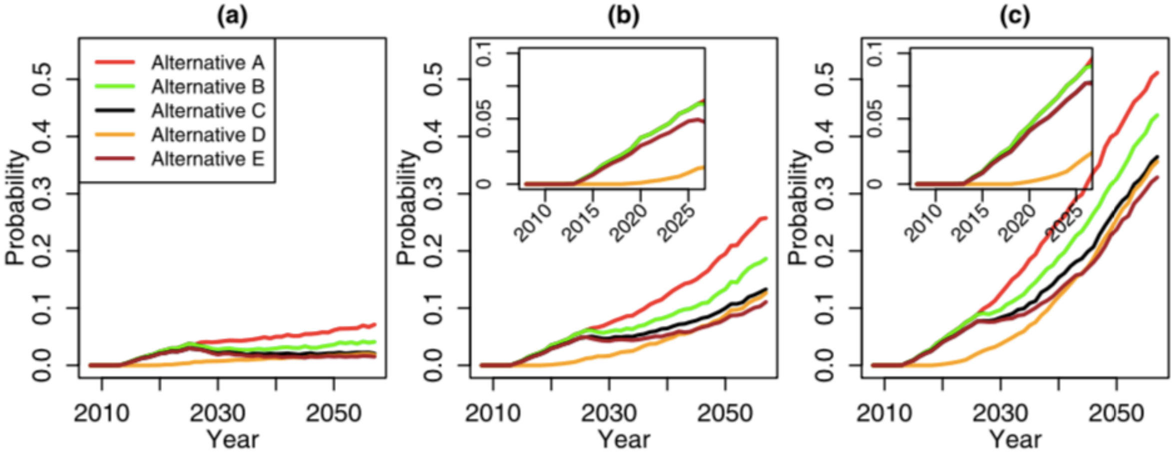

Figure 4: Risk of drying (depleting active system-wide reservoir storage in a given year) for five management alternatives under assumptions of no climate change – induced average flow reduction with an initial demand of 13.5 MAF. (b) Same as Figure 2a but for natural climate variability and a superimposed 10% reduction in the annual average inflow over the 50-year period. Inset shows the risk in the near term for the period 2008–2026. (c) Same as Figure 2b but for 20% reduction in annual average inflow. *[Source: Rajagopalan 2009]*

MANAGEMENT METHODS

Water shortage typically leads to mandatory curtailments on allotted water. In California, apportionment occurs on the basis of reasonable use; however, this management method relies on an interpretation of a dated set of conflicting water laws and often leads to litigation calling into question the legality of curtailment and the definition of reasonable use (Hanak et al. 2011). Researchers appear to be in consensus that demand reduction is one of the most effective and cost efficient options for addressing shortage (Dettinger 2015; Overpeck & Udall 2010; Rajagopalan 2009). This is easier said than done. An alternative, or perhaps additional, recourse is to build a portfolio of flexible solutions. Many states have already started experimenting with and implementing different options.

Existing Water Management

Drought issues faced by the West have occurred before and Dettinger et al. (2015) suggest institutional knowledge allows managers to understand the multitude of options for future management. Depending on the region in question, these options encompass both agricultural and urban solutions.

The 2003 quantification settlement agreement (QSA) was a 15 year program implemented to redistribute water allocated to San Diego, CA as part of a mitigation effort for the Salton Sea. Negotiated between the Imperial Irrigation District (IID) and San Diego Water Authority, the program incorporated a fallowing program where farmers were paid per acre-foot of water according to a price set by the IID Board of Directors (Imperial 2018). It also included a provision to limit participation to three out of every five years, likely to manage budget and encourage rotation among farmers participating. These sorts of fallowing schemes have frequently been criticized and referred to as “buy-and-dry” programs (Fleck 2016; Castle 2016). Opponents argue the programs are time consuming, expensive, and incentivizes a permanent transaction, thus eliminating agriculture.

An alternative agriculture-to-urban transfer option was studied in 2007 by Khaled Bali, a University of California researcher (as referenced in Fleck, 2016). Bali examined the effects of deficit irrigation (i.e. suspending irrigation) on alfalfa crops. Demands for cuts to alfalfa crops are a common refrain within circles pushing for agricultural water curtailments due to its high consumptive use; however, alfalfa is a resilient crop. Bali demonstrated that, while deficit irrigation reduced yield, it did not kill the plants. The study suggests compensating farmers for the loss in yield, rather than for the water, for intentional use of deficit irrigation. The estimated savings for implementation across Arizona and Colorado is “nearly four times as much water per year as the annual consumption of the Las Vegas metro area” (Fleck 2016, pg. 28).

This estimate is perhaps deceptive because Las Vegas has taken extensive measures to reduce water use and implement systems for conservation and recycling. The city is among the leading examples in the West. From 2002-2013, its population increased by 34% while its use of Colorado River water decreased by 26% (Fleck 2016). Actions taken to achieve this feat include using brackish water in all fountains, increasing the use of drip systems in lieu of sprinklers on golf courses, paying residents to tear out their lawns, and restricting allowed landscaping in new developments. They also process sewage and return it to Lake Mead, just upstream from the city. In this way, the water used by residents can be viewed as borrowed rather than consumed.

Future Colorado River Management

Grafton et al. analyzed the effects of water use, climate change, and governance on four river systems around the world, including the Colorado River (2012). The authors concluded the consumptive use of water in each of the four systems remained the largest threat to water supply, even considering climate change. While a reduction in demand, analogous in this case to consumptive use, remains challenging, Grafton et al. suggest several ways to transition to in-stream use based on their study.

With shortage frequency increasing, the growing crisis is a potential tool to motivate action. The authors suggest conducting a comprehensive evaluation of the economics of ecosystem services and consumptive use as well as the implementation of water markets. With a value assigned for ecosystem services, the study suggests the variability of water reliability is more likely to be divided between water users and environmental flows. Finally, Grafton et al. recommend administration of water through centralized and nested water governance structures within basin-wide management systems.

Integration of agencies can already be seen through a number of initiatives in the West, which can be used as templates. For example, at the state level, the *Public Health Impacts of Climate Change in California: Community Vulnerability Assessment and Adaptation Strategies* report resulted from an NGO to government partnership between the Natural Resources Defense Council (NRDC) and the California Department of Public Health (CDPH) and the Public Health Institute. At the national level, the Western States Water Council (WSWC) and 11 Federal agencies partnered in 2008 through the Western Federal Agency Support Team (WestFAST) to produce joint work plans to address climate change, water availability and use, and water quality (Bierbaum 2013).

The plans being developed in these partnerships often incorporate a structure for adaptive management as more information on governance outcomes becomes available. This structure provides states and municipalities increased flexibility to implement conservation efforts that work, like those discussed in the previous section.

Lastly, policymakers need the ability to make informed decisions motivated by sound, shared science. Promoting an open exchange of information, especially among signatories of the Colorado River Compact, will facilitate these policy decisions. To deliver actionable data, agencies and industry will need to continue support for research, especially refinement of global climate models and hydrologic models. This continued progress will increase the reliability of GCM models and paleoclimate chronologies to better understand drivers of changing streamflow.

CONCLUSIONS

Projections of variability in Colorado River flow will require increased flexibility for management and reductions in water demand. Dendrochronological flow reconstructions demonstrate the potential severity of any future drought, which could last from multiple decades to centuries. While these flow chronologies are informative, assuming future action should be motivated purely based on stationarity is not prudent as demonstrated by the over allocation of the Colorado River Compact. Anthropogenic factors have been shown to affect climate change, specifically impacting temperature and precipitation. The effect of climate change on precipitation is less clear and presents an opportunity to refine global climate models to improve forecasting. Temperature impacts are widely accepted among researchers and demonstrate a measurable mean streamflow loss in the Colorado River by midcentury. Preparation for potential flow losses will require adaptability and cooperation among future water managers and governing agencies. Increased funding for research will support policymakers in their decisions.

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Appendices

Appendix A

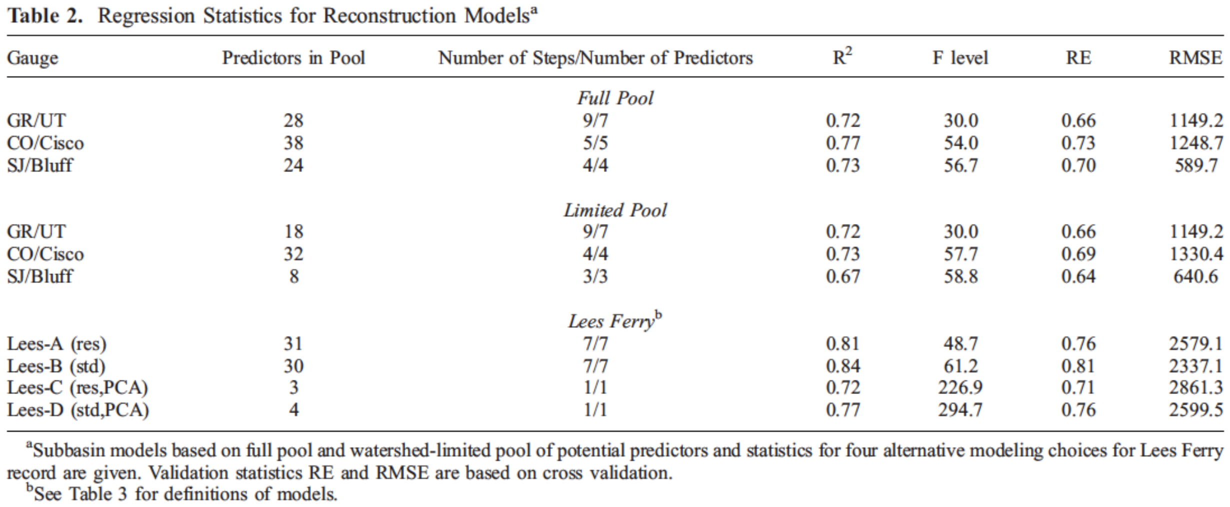

Table 2. Regression Statistics for Reconstruction Models[a]

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.

Source: Woodhouse et al. 2006

Appendix B

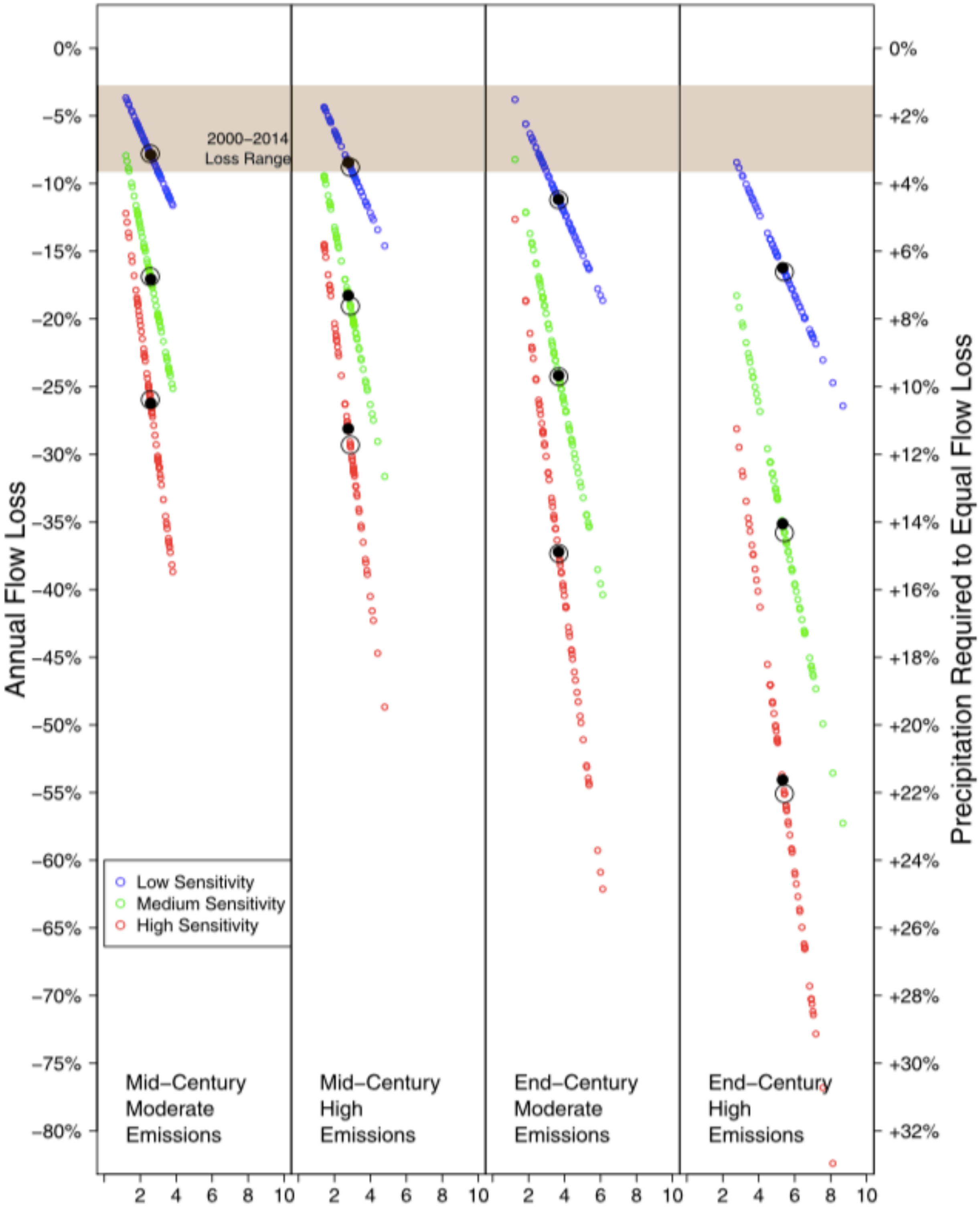

Figure 5. Temperature-induced flow losses by model run (one per dot) with temperature increases shown on horizontal axis. For each period (midcentury, end-century) and emissions type (moderate, high), flow losses for each model run are shown with the 3 (low 5 23%/ 8C, medium 5 26.5%/8C, high 5 210%/8C) temperature sensitivities. Black dots/circles are averages/medians for each sensitivity. Precipitation increases needed to counteract flow losses at right are based on 2.5 precipitation elasticity. Ranges for the temperature-induced losses during 2000–2014 drought are shown in shaded brown at the top (supporting information Text S5). *[Source: Udall & Overpeck 2017]*