A New Approach for Using Tree-Ring Data in Water Management Planning on the Colorado River

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INTRODUCTION

The Colorado River is the major water source for the semiarid regions of western United States. The foundation of the water delivery system are the two massive reservoirs, Lakes Powell and Mead, which are capable of storing up to 60 maf, or four years of average Colorado River flow[1]. Recently, the storage system was tested. After about ten years of below-average flow, deliveries continued uninterrupted. As a result, however, the system now exists in its most vulnerable state ever. The threat is three-pronged: 1) combined storage of the two reservoirs is hovering around an all-time low[2]; 2) population, and therefore demand, levels in the basin are at an all-time high; and 3) climate change models have projected further decreases in Colorado River streamflow (eg., Seager et al 2007, Christensen and Lettenmaier 2007, Gao et al 2011).

Addressing these threats, and reducing vulnerability, is likely to require a policy solution. The Colorado River system is managed under the auspices of the "Law of the River," a legal framework comprised of over 100 rules and regulations. Formerly, the Law of the River was not considered flexible enough to accommodate change. In 2007, however, a new set of management guidelines were collectively developed by Reclamation, the Basin States and many different stakeholder groups in response to drought conditions at the turn of the century. Amongst the new measures introduced was a provision to reduce deliveries to the Lower Basin[3] based on pre-determined levels of storage, indicated by Lake Mead elevation. Table 1 shows the reductions in allocations incurred at each designated Lake Mead elevation, i.e., "trigger" elevation. The shortage guidelines are significant because they potentially enable the Lower Basin states to anticipate, and thereby plan for, the amount of shortage and when shortage might occur. They are also significant because they, in conjunction with the other provisions introduced in 2007, are interim in nature, to be applied only through 2026[4]. Furthermore: "Beginning no later than December 31, 2020, the Secretary [of the Interior, represented by the Bureau of Reclamation] shall initiate a formal review for purposes of evaluating the effectiveness of these Guidelines." The review, to be conducted in consultation with the Basin States, will presumably be the basis for Colorado River management post-2026.

In this era of uncertainty, decision makers must think strategically about future policy. Science can play an important role but in order for science to inform policy, information must be appropriate and provided on scales that are relevant to management (Jacobs and Pulwarty 2003). In this study, we deploy a novel, yet simple, application of paleodata and embed it in an analysis framework customized for the evaluation of the Interim Guidelines. A tree-ring reconstruction of Colorado River streamflow at Lees Ferry is used to simulate plausible future hydrologies. In

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[1] Computed from 20th century data.

[2] On Nov. 30, 2010 Lake Mead reached 1,081.94 ft (329.78 m), setting a new record monthly low. U.S. Department of the Interior, Bureau of Reclamation. "Lake Mead at Hoover Dam, Elevation". Retrieved February 17, 2011.

[3] California, Arizona, and Nevada.

[4] Secretary will consult with BS if LM takes a dive below 1025 to discuss implementation of the guidelines (USDOI 2007: 7.B.4).

comparison to instrumental data, tree-ring data have a wider range of variability both in sequence and mean level of flow. In comparison to stochastic data, tree-ring data can be related to wider patterns and physical processes. Tree-ring reconstructions have been widely applied for many uses in western water management, especially the Colorado River Basin (see Meko and Woodhouse 2011 for review). Two approaches are common. In the first case, the period with the lowest mean streamflow is used to drive management models. This provides managers with an idea of system behaviour under a "worst case" scenario. The shortcoming of this approach is that only one sequence is examined. Different sequences with the same mean streamflow could have a significantly different effect on the system. Examining only a single sequence also precludes the possibility of evaluating system response in a probabilistic context. In the second case, the entire paleorecord is used. Here, probabilities can be computed but the impacts of record segments with mean streamflow much higher or lower than average, as well as novel sequences within segments, can be difficult to discern. In this research, we have identified periods of the paleorecord with similar but lower-than-average mean streamflow. These segments are then grouped and taken to represent different future streamflow scenarios.

In this study, our goal is to highlight characteristics of system behaviour in the coupled system of basin hydrology and the management system. We achieve this by utilizing the natural variability represented in the paleorecord. In particular, we identify "paleo-scenarios" by identifying segments of the paleo record with streamflow levels that are less than current levels to yield "worsening-case scenarios" and develop a more structured view of system vulnerabilities.

METHODS & MATERIALS

We used the Colorado River Simulation System (CRSS), Reclamation's official long-term planning and policy model. CRSS is an object-oriented model where objects represent the different entities that comprise the Colorado River system, eg., users, channels, canals, and reservoirs. CRSS simulates system behavior by emulating individual object behaviors as well as the interactions between and among objects. The overarching rules that govern these interactions are based on a detailed portrayal of the "law of the river," a compendium of over 100 laws and regulations. The rules in CRSS are updated for any modifications in the "law of the river" as they arise. We obtained, from Reclamation, the current version of CRSS which contains the most recent management guidelines, implemented in 2007 (USDOI 2007). Initial reservoir conditions within the model were set for December 31, 2011 as projected by the July 24-month study model, Reclamation's mid-term management model.

We analyzed a 30-year management horizon which is consistent with typical longer-term management horizons. In the context of this study, the 30-year window gives water managers and decision makers a view of system function and reliability under the conditions that the current guidelines continued unchanged for another 15 years. CRSS steps through each 30-year segment in the paleorecord sequentially. Thus for a 1243-yr record, there are 1214 possible 30-yr segments.

CRSS is forced using monthly naturalized streamflow values for a set of 29 input nodes located throughout the basin, 20 in the upper basin and 9 in the lower basin. The streamflow data used in this analysis is a reconstruction of naturalized flow at Lees Ferry and spans 1244 years, from 762 to 2005 (Meko et al 2007). It can be downloaded from the International Tree-Ring Data Bank (ITRDB) (http://www.ncdc.noaa.gov/paleo/treering.html). To input into CRSS, reconstructed streamflow data were disaggregated both temporally and spatially by applying the same nonparametric approach used by Reclamation (Prairie et al 2007). Annual reconstructed flows were disaggregated into monthly flows for all 29 input nodes.

System vulnerabilities were defined as shortages to the Lower Basin. Current management guidelines outline the level of shortage incurred for set Lake Mead trigger elevations (USDOI 2007). Annual deficits were computed based on simulated Lake Mead elevations (output from CRSS) and associated delivery cuts (Table 1). For each 30-year period, annual deficits were summed over the paleo-segment to get total accumulated deficit.

Scenarios were selected to reflect a range of possible futures, including the projected decreases in Colorado River streamflow based on the latest GCMs. We examined four scenarios identified by mean streamflows of: 1) 15.0 maf; 2) 14.5 maf; 3) 14.0 maf; and 4) 13.5 maf. The relationship between streamflow and total deficit was characterized in two ways. First, streamflow sequences from the 30-yr periods with the ten highest and ten lowest total deficit were compared. Median streamflow was computed for each endmember group for each of the paleo-scenarios. Second, the covariation of streamflow and total deficit was characterized using both correlation and regression analysis. In the correlation analysis, we incrementally compared mean streamflow with the cumulative amount of delivery reductions over the course of the 30-yr management period. Within each segment, mean streamflow was computed for the first "n" years in the management horizon, where n = 1 to 30. For example, an n = 10 represents the mean streamflow of years one through ten; an n = 11 represents the mean streamflow of years one through eleven, and so on. Each segment is thus described by 30 mean streamflow levels. The Spearman rank correlation coefficient was then computed between mean streamflow at each increment and the total deficit, yielding a total of 30 correlation coefficients. Regression models were developed for each scenario based on mean streamflow at nine years. We selected mean streamflow at nine years as a predictor to conform to policy schedules within the Basin. As stated earlier, the current guidelines are interim in nature and are set to be evaluated by 2020, the ninth year in our CRSS runs. Our objective here was to simulate the potential level of predictability that decision makers might encounter given a designated level of streamflow.

RESULTS

Mean streamflow in the paleo-record

For all 30-year segments in the paleorecord, mean streamflow ranged from 12.85 to 16.45 maf. 30-year segments with a mean level of 14.5 maf (+/- 0.25 maf) were the most frequent in the paleorecord (Figure 1). Total accumulated deficit for the 30 year segments ranged from no shortage to a maximum of 13.17 maf (0.44 maf/year). Shortage does not occur in about 18% of the segments (215/1214). Mean streamflow for these segments ranged from 14.49 to 16.45 maf. The 10 largest total deficits are greater than 12.75 maf and cluster during two periods in the paleorecord: the mid-1100s and the late 1800s (Figure 2). For the entire paleorecord, mean streamflow and total deficit have a correlation coefficient of -0.73 but for any particular level of mean streamflow total deficit can range up to 11 maf (Figure 3).

Paleo-scenarios

Descriptive statistics for each of the four scenarios can be found in Table 2. The number of segments in each of the four hydrologic scenarios varied. Segments with a mean of 13.5 maf (SC135) had the lowest with just under 100 and segments with a mean of 14.5 maf (SC145) had the most with over 350. Among the two drier scenarios, SC135 and segments with a mean of 14.0 maf (SC140), shortage occurred in all segments. For the driest scenario, SC135, 99% of the segments ended in shortage with Lake Mead at elevations lower than 1075ft. In contrast, for the wettest scenario, segments with a mean of 15.0 maf (SC150), only about one-quarter of the segments ended in shortage. In other words, system recovery occurred in 75% of the segments.

Total deficits for each paleo-scenario

The distribution of total deficit within each of the scenarios is illustrated in Figure 4. For the wettest scenario, mean streamflows of 15.0 maf, total deficits range from 0 to about 6 maf with the 50% non-exceedence level dropping down at about 1 maf, indicating that there is a 50% chance that total deficit accumulated over the 30-year management horizon will not be more than 1 maf. For the driest scenario, mean streamflows of 13.5 maf, total deficits range from about 2 to 13.5 maf with the 50% non-exceedence level dropping down at about 7.5 maf. The 50% non-exceedance for total deficit increases by roughly a factor of two for every decrease of 0.5 maf in mean inflow.

Streamflow and total deficit
Correlation/Regression analysis

In all cases, mean streamflow over the entire 30-yr period shows no correlation with total deficit. Imbedded within the 30-yr period, however, are windows of varying lengths having significant correlations with total deficit. The shortest window occurs in SC135, where mean streamflow from the first 9 years shows a -0.73 correlation with total deficit (Figure 5). Minimum correlation with other windows are -0.70, -0.65, and -0.5 for SC140, SC145 and SC150, respectively. In addition to showing stronger correlations, the drier scenarios also show minimum correlations earlier in the management window. This suggests that for drier scenarios, total deficit at the end of 30 years can be predicted as earlier as nine years into the management window.

Regression models were developed for each of the scenarios using mean streamflow over the first nine years as a predictor of total deficit. Only for SC135 does a window of nine years reflect minimum correlation (see Figure 5); for all other scenarios the 9-yr window is an inferior predictor. The purpose, however, of targeting the 9-yr window is to simulate the information that might be available to decision makers in the Colorado River Basin in 2020 when the Basin States and interested stakeholders meet to evaluate current guidelines and establish future guidelines. All models are significant at the $p<.0001$ level. As expected, however, the highest variance explained is for the SC135 model, where mean streamflow explains about half of the total variance in total deficit. The lowest variance explained is about 5% in the SC150 model. In contrast to the relationship of total deficit with 30-yr mean streamflow for the full paleodata set (Figure 3) where minimum and maximum total deficit can differ up to 11 maf for any given streamflow level, the SC135 model differs up to 4 maf, excluding outliers. The only other model which presents an improvement, albeit small, over the full paleodata set is the SC140 paleoscenario.

End-member analysis

Analysis of streamflow for periods with the 10 highest and lowest deficits within each scenario indicated a consistent pattern across three of the four scenarios. For the set of sequences that comprise the scenario, those sequences that begin with higher-than-average flows, based on the respective scenario, tend to incur the least amount of deficit compared to those sequences that begin with a series of years with lower-than-average flows. Moreover, each scenario appears to have a different length window that is associated with final deficits. For instance, in the driest scenario, streamflow levels in the first 5-6 years appear to signal whether relatively high or low deficit will be incurred by the end of the 30-year period (Figure 7). When streamflow during this initial period is higher than average, in this case 13.5 maf, total deficits will be the lowest for the scenario; the converse is true when streamflow levels during the first 5-6 years are lower than average. For increasingly wetter scenarios, when mean streamflow is 14.0 and 14.5 maf, the window differentiating the lowest or highest deficits expands to about nine and twelve years, respectively. This pattern is not evident for the wettest scenario where mean streamflow is 15.0 maf.

DISCUSSION

This paper presents a novel method for incorporating paleodata into water planning for the Colorado River Basin. It introduces two unique features. First, instead of using either single sequences, i.e., worst case scenario, or the full data set to evaluate system vulnerability, we have targeted a subset of sequences within the paleorecord with similar mean streamflow. The strength of this approach is that it takes into account how order of streamflow magnitude within the sequence impacts system vulnerability. In previous studies related to climate change planning in the Colorado River Basin, sequence is often only acknowledged as an important factor with no supporting analysis (Christensen and Lettenmaier 2007). The second unique feature of our approach is that we use a system variable, *total deficit*, to organize and prioritize streamflow information that could be useful to water planners and policy makers. Future shortage constitutes a significant vulnerability to the Lower Basin and therefore is of interest to water managers. Information regarding the characteristics of hydroclimatic drivers associated with specific levels of shortage severity should serve water planners and policy makers well in informing decisions regarding current and future water use in the Lower Basin.

This approach was implemented using a streamflow reconstruction (Meko et al 2007) to drive Reclamation's official long-term planning and policy model, CRSS. Results indicate that annual streamflow sequence can have a significant effect on level of deficit. For any given level of 30-yr streamflow, sequence can account for differences of up to 11 maf in total deficit. This range is narrowed when the timing and magnitude of drought and pluvial events within 30-yr horizons is taken into account. Analyses of sequences within each paleo-scenario indicate that for current reservoir conditions, streamflow levels early in the management period are strongly related to total deficit at the end of the management period. For drier scenarios, the window of association is shorter than for wetter scenarios, nine and 22 years, respectively. Moreover, drier scenarios had stronger associations than wetter scenarios. These results highlight two important features of the Colorado River system: 1) current reservoir conditions dictate that streamflow levels over the next decade can be informative in projecting deficit levels 30 years into the future; and 2) under drier streamflow regimes, the ability to project future deficit increases. As the hydrological regime becomes drier, the importance of streamflow increases. This reflects the negative impact of low storage levels on the ability of the system to buffer streamflow variability. In other words, as the Colorado River Basin moves into a drier hydrological regime, the system will become more susceptible to fluctuations in streamflow. While, this is not new information, this study offers some insight into the level of vulnerability that might develop.

For water managers in the Colorado River Basin, the implications of this analysis can be significant. If there is a shift to drier conditions, then mean streamflow over the next 10-20 years could be used to indicate deficits that may be incurred by the Lower Basin over a 30-yr period. This lead time could be useful for planning purposes and reducing vulnerability. It is, however, important to keep in mind that this approach, as it is based on paleo-analogs, has its limitations. We are deploying the variety of sequences found in this over 1200-year reconstruction to establish a range of possible futures. However, paleo-analogs are only an approximate match for future conditions under a regime of changing climate (Woodhouse et al 2010). Various factors, both climatic and non-climatic, could coalesce to create sequences unseen in the paleo-record, even one over 1000 years long.

LITERATURE CITED

Christensen, N. S. and Lettenmaier, D. P. 2007. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin. *Hydrology and Earth Systems Science*, **11**, 1417–34.

Gao Y, JA Vano, C Zhu, and DP Lettenmaier, 2011: Evaluating climate change over the Colorado River basin using regional climate models, *J. Geophys. Res*., **116**, D13104, doi:10.1029/2010JD015278.

Jacobs, K. and R. Pulwarty, 2003. Water Resource Management: Science, Planning and Decision-Making. In: *Water: Science, Policy, and Management: challenges and opportunities*, Richard G. Lawford, Denise D. Fort, Holly C. Hartmann, and Susanna Eden (editors). American Geophysical Union, Washington, D.C. pp.177-204.

Meko, D.M. and C.A. Woodhouse, 2011. Dendroclimatology, dendrohydrology, and water resources management, In: *Tree Rings and Climate: Progress and Prospects* (eds. M.K. Hughes, T.W. Swetnam, H.F. Diaz). Springer, pp. 231-261.

Meko, D. M., C.A. Woodhouse, C.H. Baisan. *et al*. 2007. Medieval drought in the upper Colorado River basin. *Geophysical Research Letters* 34 , L10705, doi: 10.1029/2007GL029988

Prairie, J.R., Rajagopalan, B., Lall, U. and T. Fulp. 2007. A stochastic nonparametric technique for space-time disaggregation of streamflows. *Water Resources Research* 43(3), doi: 10.1029/2005WR004721

Seager R., Ting M., Kushnir Y., Lu J., Vecchi G., Huang H-P, Harnik N., Leetmaa A., Lau N-C, Li C., Velez J. and Naik N. 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science*, 316, 1181–1184.

USDOI (US Department of Interior) 2007. *Record of Decision. Colorado River Interim Guidelines forLower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead* . Washington, D.C. , December. http://www.usbr.gov/lc/region/programs/strategies/RecordofDecision.pdf .

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

TABLES

Table 1. Shortage triggers and allocations to the Lower Basin states.

Lake Mead elevation	California (maf)	Arizona (maf)	Nevada (maf)	Total (maf)
>1075	4.400	2.800	0.300	7.500
1075≥1050	4.400	2.480	0.287	7.167
1050≥1025	4.400	2.400	0.283	7.083
<1025	4.400	2.320	0.280	7.000

Table 2. Descriptive statistics for the four different scenarios.

"SC135" is all segments with mean of 13.5 maf; "SC140" is all segments with mean of 14.0 maf; "SC145" is all segments with mean of 14.5 maf; "SC150" is all segments with mean of 15.0 maf.

Scenario	No. Segments	No. (%) with NO shortage	No. (%) ending on shortage
SC135	98	0	97 (99.0)
SC140	182	0	159 (87.4)
SC145	358	9 (2.5)	233 (65.1)
SC150	306	71 (23.2)	79 (25.8)

FIGURES

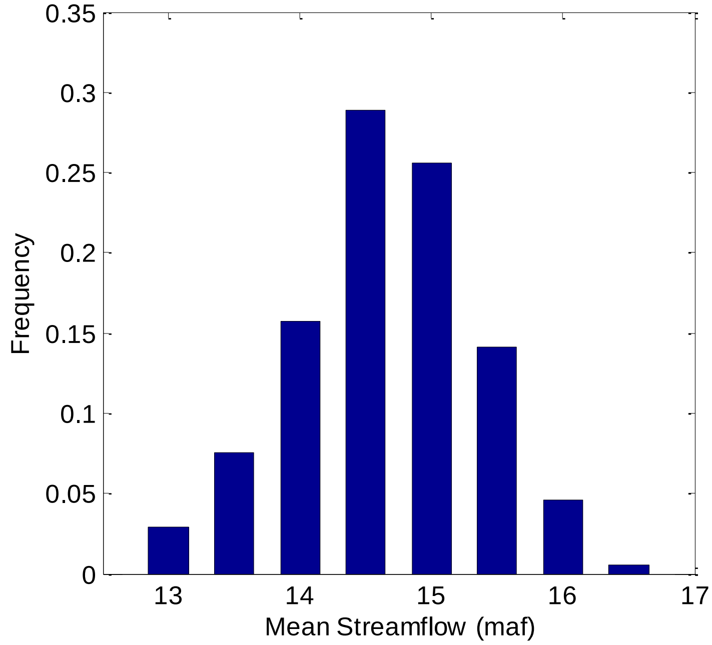

Figure 1. Frequency of 30-yr segments with specified mean streamflow.

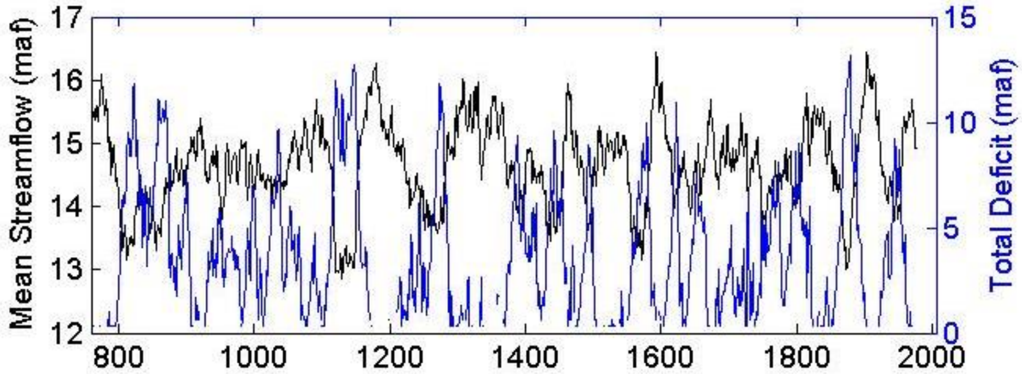

Figure 2. Time series of total 30-yr deficit and running 30-yr mean.

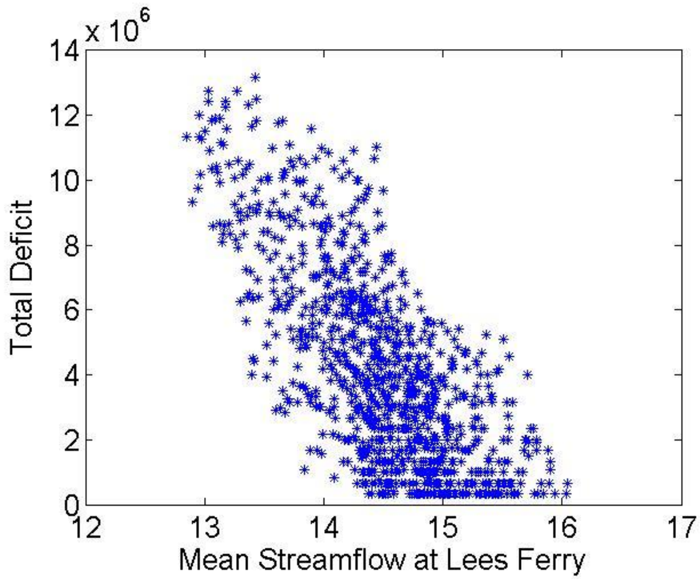

Figure 3. Relationship between mean streamflow (maf) and total deficit (maf).
30-yr mean streamflow (maf) at Lees Ferry and total deficit (maf) at the end of the 30-yr period.

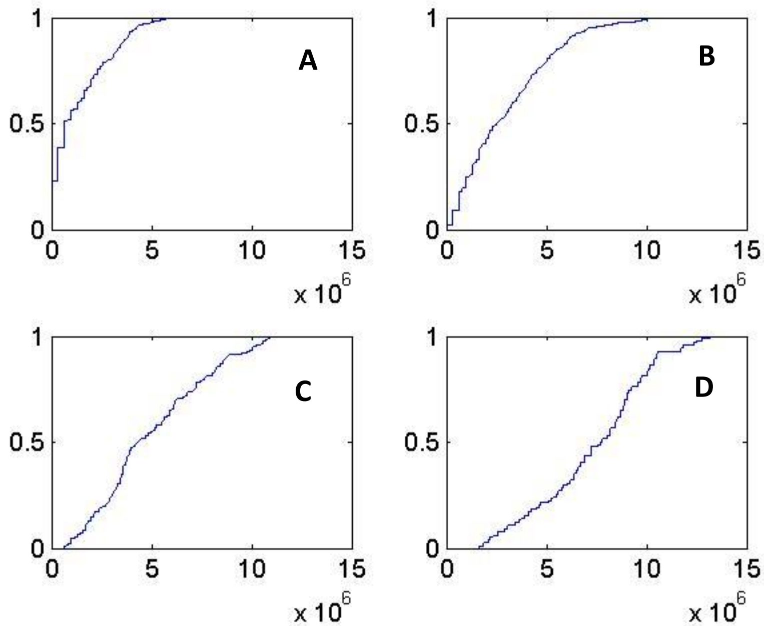

Figure 4. Cumulative distribution functions for each of the four scenarios.
A) SC150; B) SC145; C) SC140; D) SC135.

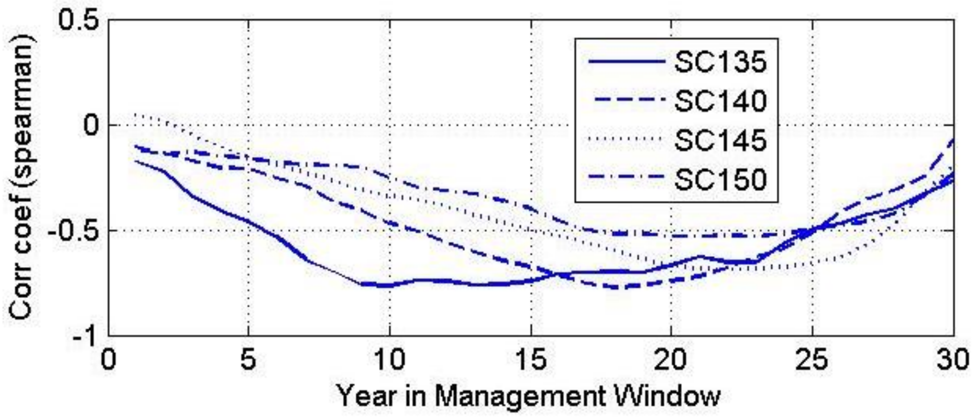

Figure 5. Incremental correlations

Incremental correlations between mean streamflow at each year in the management window and total deficit for the 30-yr segment for all four scenarios.

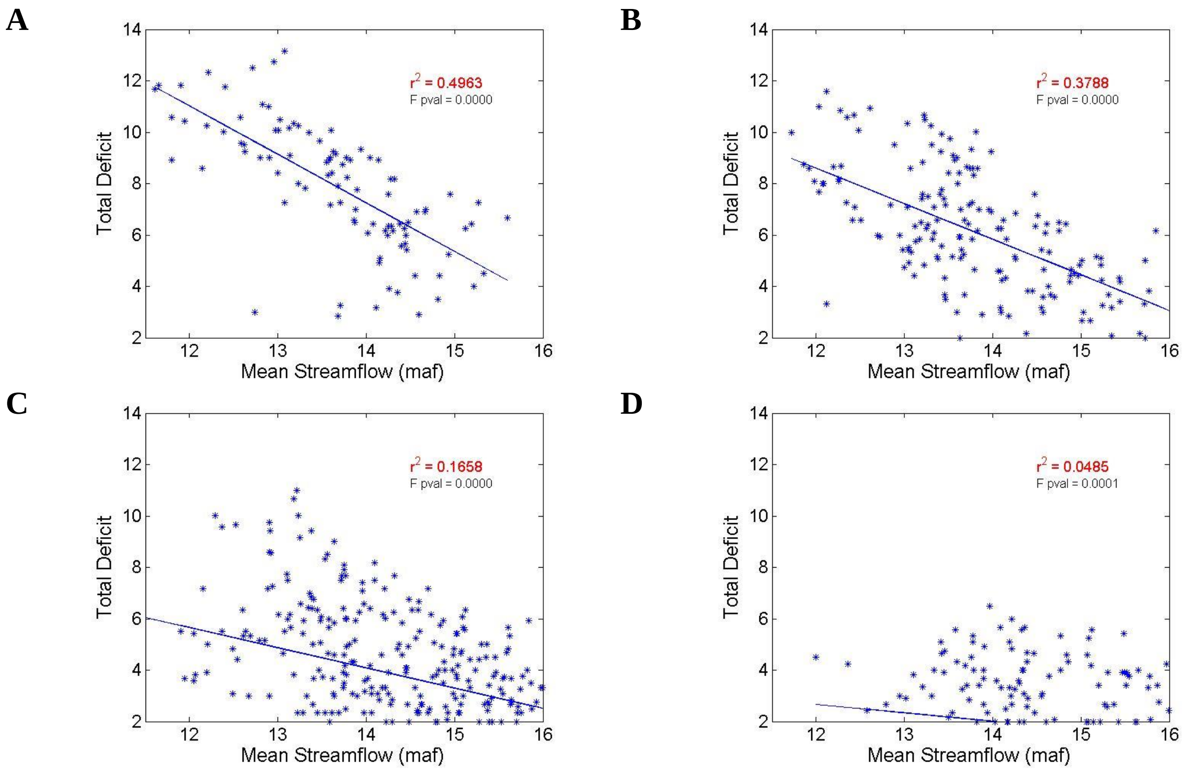

Figure 6. Regressions between mean streamflow and total deficit.

Regressions between mean streamflow of the first nine years and total deficit after 30 years for each paleoscenario: A) 13.5 maf; B) 14.0 maf; C) 14.5maf; and D) 15.0 maf.

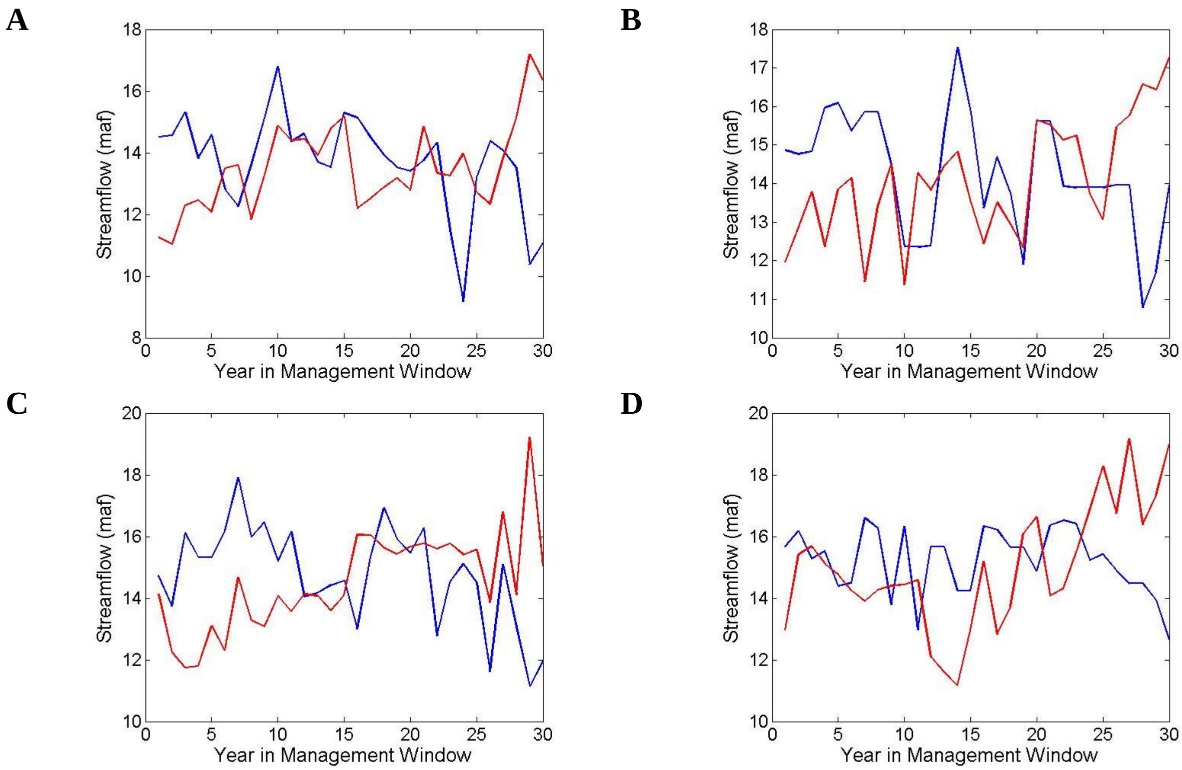

Figure 7. Median streamflow for highest and lowest streamflows.

Median streamflow for 10 30-yr periods with highest (red) and lowest (blue) total deficits for each paleo-scenario: A) 13.5 maf; B) 14.0 maf; C) 14.5maf; and D) 15.0 maf.