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Key Points:
- Colorado River runoff efficiency can be skillfully reconstructed from the cool season precipitation and annual streamflow
- Compared to prior centuries, the 20th century contains twice as many years with high flows but low runoff efficiency
- Temperature, affecting runoff efficiency, has conditioned the impacts of droughts and pluvials on Colorado River flows over past centuries

Supporting Information:
- Supporting Information S1
- Data Set S1

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Investigating Runoff Efficiency in Upper Colorado River Streamflow Over Past Centuries

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Abstract With increasing concerns about the impact of warming temperatures on water resources, more attention is being paid to the relationship between runoff and precipitation, or runoff efficiency. Temperature is a key influence on Colorado River runoff efficiency, and warming temperatures are projected to reduce runoff efficiency. Here, we investigate the nature of runoff efficiency in the upper Colorado River (UCRB) basin over the past 400 years, with a specific focus on major droughts and pluvials, and to contextualize the instrumental period. We first verify the feasibility of reconstructing runoff efficiency from tree-ring data. The reconstruction is then used to evaluate variability in runoff efficiency over periods of high and low flow, and its correspondence to a reconstruction of late runoff season UCRB temperature variability. Results indicate that runoff efficiency has played a consistent role in modulating the relationship between precipitation and streamflow over past centuries, and that temperature has likely been the key control. While negative runoff efficiency is most common during dry periods, and positive runoff efficiency during wet years, there are some instances of positive runoff efficiency moderating the impact of precipitation deficits on streamflow. Compared to past centuries, the 20th century has experienced twice as many high flow years with negative runoff efficiency, likely due to warm temperatures. These results suggest warming temperatures will continue to reduce runoff efficiency in wet or dry years, and that future flows will be less than anticipated from precipitation due to warming temperatures.

1. Introduction

With increasing concerns about the impact of warming temperatures on water resources, more attention is being paid to the amount of runoff that precipitation yields, and how and why this varies. These variations can be evaluated by assessing the relationship between runoff and precipitation, or runoff efficiency. A number of factors, including land use practices and groundwater withdraws, as well as climatic variability and change, can cause variations in runoff efficiency (e.g., Frans et al., 2013; Gupta et al., 2015; Lehner et al., 2017; McCabe & Wolock, 2016). These often, but not always, impact runoff efficiency through changes in evapotranspiration (e.g., vegetation changes due to agriculture or land clearing, increases in evapotranspiration due to warming), which in turn, are often associated with changes in temperature. While a standard definition of runoff efficiency is the ratio of the volume of runoff for a given area to the volume of precipitation over the same area, typically for a period of time such as the water year (e.g., McCabe & Wolock, 2016), we apply this concept more broadly using the difference between precipitation and streamflow to estimate the sign and relative magnitude of runoff efficiency departure.

The major rivers of the southwestern U.S., the Colorado, and Rio Grande, have been the focus of several recent studies that have examined runoff efficiency and the impact of temperature on runoff. In a study of the upper Colorado River basin for the years 1906–2006, Nowak et al. (2012) found that runoff efficiency is only weakly associated with precipitation, but strongly correlated with temperature, thus confirming that precipitation potential for generating runoff is regulated by temperature. They estimate a 2% reduction in runoff efficiency with each 1°C of warming, resulting in a decrease in annual Colorado River streamflow of slightly less than 14%. Udall and Overpeck (2017) found that unusually warm temperatures over the recent 15 year period of drought, 2000–2014, have been responsible for approximately 30% of the reduction in Colorado River flows, which have been 19% below historical average flows over this time period. This is in contrast to the 1950s drought, which was drier but cooler, with generally higher runoff efficiency for the

Colorado River (Nowak et al., 2012, see Figure 8). Udall and Overpeck (2017) suggest the projected increase in warming has the capacity to reduce flows by 20% by midcentury, clearly influencing runoff efficiency, even if offset somewhat by precipitation increases.

As part of a U.S.-wide study that evaluated trends in runoff efficiency from USGS gage data compared to those estimated from a monthly water balance model, McCabe and Wolock (2016) report an increasing, but nonsignificant trend in runoff efficiency over the years 1951–2012 for the region that includes most of the headwaters of the Rio Grande and Colorado River. They attribute positive runoff efficiency trends to climate, but in contrast to the results of Nowak et al. (2012), they find that most of the variance in runoff efficiency is explained by precipitation, and very little by temperature. McCabe and Wolock (2016) acknowledge the monthly water balance model does not reflect long-term effects of water storage, which might obscure variations at decadal or longer time scales.

The efficiency of cool season precipitation relative to Colorado River total water year runoff over the instrumental period (1906–2012) was assessed by Woodhouse et al. (2016), using a measure of difference instead of a ratio, to estimate runoff efficiency. They found that while cool season precipitation explains about two-thirds of the variation in Colorado River water year streamflow, in years when streamflow and cool season precipitation have the largest difference, runoff season (March–July) temperature explains over 40% of the variance in streamflow, while variance explained by cool season (October–April) precipitation is reduced to 19%. Low flow years with less streamflow relative to precipitation tend to be very warm during the runoff season (e.g., the 1980s–1990s and 2000s droughts), while high flow years with more streamflow relative to precipitation tend to be quite cool. However, there are also low flow years in which flows are higher than might be expected given precipitation amounts, such as the 1950s drought, when runoff season temperatures were relatively cool. Since the 1980s, Colorado River streamflow has been lower than expected relative to precipitation totals, indicating runoff efficiency has decreased. These results from a difference-based measure of runoff efficiency coincide relatively well with the runoff efficiency based on the ratio of flow to precipitation volume of Nowak et al. (2012), considering the difference in the precipitation season used in each study (cool season versus annual). In addition, the relationship between runoff efficiency and residual temperature (with the dependence on precipitation removed) in the two studies is comparable ($r = -0.45$ versus $r = -0.49$), suggesting the influence of temperature is quite similar in the two measures of UCRB runoff efficiency. There is a close correspondence between UCRB runoff efficiency generated using the ratio of flow to precipitation and runoff efficiency based on the difference ($r = 0.82$), but the two runoff efficiency metrics highlight different characteristics. Difference-based runoff efficiency emphasizes the nature of the departures between flow and precipitation while ratio-based runoff efficiency is more useful for assessing the interannual influence of hydroclimatic processes (for more details, see supporting information Text S1, Table S1, and Figures S1–S4).

Changing runoff efficiency in the upper Rio Grande was the focus of a recent investigation by Lehner et al. (2017), who used a Rio Grande streamflow reconstruction from 1571–1977 extended with instrumental data for 1978–2015. Here, as in other snowmelt-dominated basins, water supply forecasts typically rely on snow water equivalent (SWE) and cumulative precipitation to predict spring runoff. Lehner et al. (2017) show that runoff efficiency is nonstationary due to its sensitivity to temperature, calling into question the reliability of forecasts that are based primarily (or solely) on SWE and precipitation. Their central finding indicated a decreasing trend in runoff efficiency over the recent 30 year period, 1986–2015, which was unprecedented in the context of the last four and a half centuries. This result coincides with the experiences of Rio Grande water resource managers, who have found the accuracy of runoff forecasts has been biased high in the last decade (Lehner et al. 2017). The negative trend in runoff efficiency is also in agreement with results from Woodhouse et al. (2016) for the upper Colorado River basin. Using reconstructed upper Rio Grande water year streamflow and precipitation to extend records back to 16th century, Lehner et al. (2017) found that very high runoff efficiency values coincide with high precipitation years, and vice versa, which suggests that the 1950s drought, with a relatively high runoff efficiency (Nowak et al., 2012) is an anomalous event. In agreement with other studies (e.g., Woodhouse et al., 2016; Udall & Overpeck, 2017), they also find that low flows and low runoff efficiency values occur more often in warm years, and indicate that recent warming temperatures have been a critical component for the decreasing trend in Rio Grande runoff efficiency. However, Lehner et al. (2017) also suggest the low runoff efficiency trend of recent decades could occur under natural climate variability alone.

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Warming trends will reduce the runoff efficiency of the Colorado River in the future, further exacerbating the impacts of droughts (e.g., Nowak et al., 2012; Udall & Overpeck, 2017), and possibly biasing water supply forecasts that do not consider the influence of temperature (Lehner et al., 2017). While reductions in flow accompany all droughts, how closely coupled are dry conditions with low runoff efficiency in the Colorado River Basin? And how unusual are periods like 1950s, with low flows but relatively high runoff efficiency? Conversely, are high flows always associated with high runoff efficiency, or are there high flow years when runoff efficiency is lower? Woodhouse et al. (2016) found few instances of high flow years with low runoff efficiency until the last decades of the 20th century, raising the question as to whether or not this is a signature of anthropogenic warming. If so, the results suggest that even if future multiyear pluvial events occur in the Southwest, the capacity of these events to replenish reservoirs is likely to be diminished by warmer temperatures driving reduced runoff efficiencies.

This study focuses on the upper Colorado River basin (UCRB) to investigate the nature of runoff efficiency over past centuries (Figure 1). As a major source of water for seven western U.S. states, numerous Indian tribes, and the state of Sonora in Mexico, the Colorado River is of critical importance to both human activities and natural ecosystems. Although records of UCRB streamflow and climate exist for just over 100 years now, this period of time contains only a limited number of drought and pluvial events, and is too short for

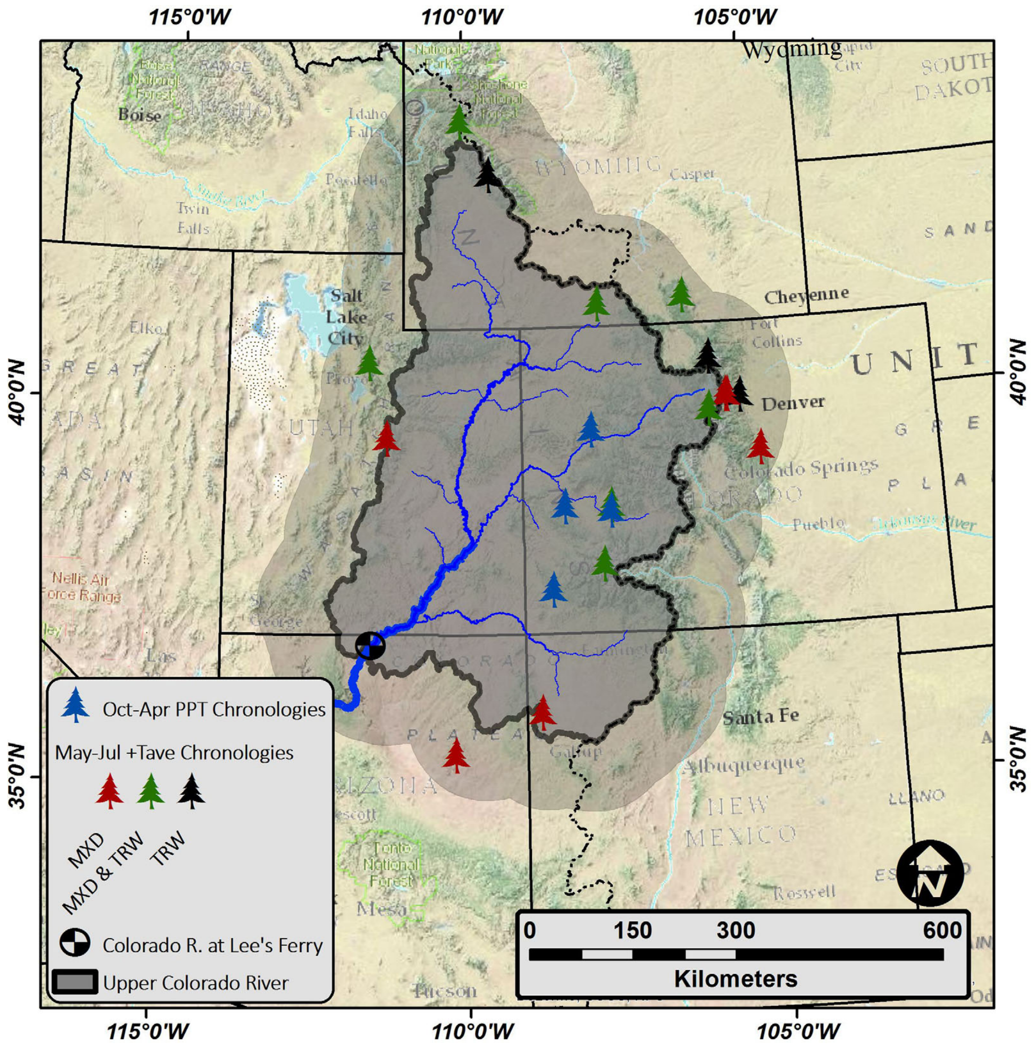

Figure 1. The network of ring-width (TRW) and maximum density chronologies (n = 23, MXD) located within 100 km of the Upper Colorado River Basin, and used to reconstruct late runoff season (May–July) average temperature (red, green, and black symbols), with tree-ring chronologies used in the cool season (October–April) precipitation reconstruction (n = 4, blue symbols).

assessing how runoff efficiency can play a role in these events. Similar to the Rio Grande work of Lehner et al. (2017), tree-ring reconstructions of streamflow and precipitation are used to extend the record of runoff efficiency back in time, in this case for the UCRB. In this study, however, we more closely examine runoff efficiency during multiyear drought and pluvial periods in annual Colorado River streamflow. Specifically, we characterize runoff efficiency through the persistence and frequency of each of four types of events: above average flows with low runoff efficiency, below average flows with high runoff efficiency, as well as the more commonly occurring low flow, low runoff efficiency events, and high flow, high runoff efficiency events. We use the runoff efficiency metric based on the difference between standardized water year streamflow and standardized cool season precipitation to build on the results of Woodhouse et al. (2016) and to highlight the characteristics of the runoff efficiency departures.

The primary objectives of the study are: (1) to assess the feasibility of using reconstructions of streamflow and precipitation to generate information on runoff efficiency for the UCRB, and (2) to investigate the characteristics of runoff efficiency over the past 400 years, but especially during major drought and pluvial events recorded in the streamflow reconstruction. Specific research questions include: Is the reduction of runoff efficiency in Colorado River flow in recent decades, in both low and high flow years, unusual in a centuries-long context, or have there been warm periods in the past in which runoff efficiency also reduced Colorado River flows? Is there evidence for higher runoff efficiency, presumably related to cooler temperatures, alleviating the impacts of past droughts, or do most droughts occur under low runoff efficiency conditions?

Addressing these objectives may help water managers anticipate the influence of temperature on runoff efficiency under different seasonal to multiyear temperature and precipitation conditions, and ultimately, the future availability of UCRB water supplies. Results provide a baseline understanding of the impact of temperature on streamflow during both wet and dry periods, and highlight the importance of considering the temperature influence on runoff efficiency in addition to measures of moisture in forecasting water supplies.

2. Reconstructing Runoff Efficiency in the UCRB

To address these objectives and questions, we applied our knowledge of the relationship between water year streamflow and total cool season (October–April) precipitation in the instrumental data to tree-ring based reconstructions of these variables to develop a reconstruction of runoff efficiency. As mentioned above, in their analysis of instrumental data, Woodhouse et al. (2016) found that cool season precipitation explains a large part of the variability in UCRB water year streamflow, while runoff season temperatures play a relatively minor role. However, in years when flows do not match precipitation closely, runoff season temperature explains a much greater proportion of the streamflow variance. Specifically, for years with a large difference between cool season precipitation and annual streamflow (greater than one standard deviation from the mean), cool temperatures appear to coincide with higher flows than expected given precipitation in both high and low flow years, while warm temperatures in low flow years result in less flow than might be expected from cool season precipitation. The case of above average flow years with less flow than anticipated from precipitation is slightly different. These years are linked to warm March conditions (instead of March–July temperatures), along with a lack of early season snow. In terms of runoff efficiency, years with less flow relative to precipitation have low or negative runoff efficiency, and those with greater flow relative to precipitation have high or positive runoff efficiency. Negative runoff efficiency can occur in high or low flow years, as can positive runoff efficiency, and these distinctions are made in the categories summarized in Table 1.

Table 1
Categories of Runoff Efficiency, Flow, and Associated Hydroclimatic Conditions, Based on Woodhouse et al. (2016)

Runoff efficiency	Water year flow/Oct–Apr precipitation combination	Hydroclimatic conditions
Positive	Flow > precipitation	
	Flow > average	Cool Mar–Jul temperatures, higher flows
	Flow < average	Cool Mar–Jul temperatures, lower flows
Negative	Flow < precipitation	
	Flow > average	Warm Mar, less early snow, higher flows
	Flow < average	Warm Mar–Jul, lower flows

We use cool season precipitation instead of annual precipitation in the definition of runoff efficiency for two reasons. Because winter snowpack is such an important component of water year flow in the UCRB, we are interested in examining contribution of this season apart from precipitation that falls during other parts of the year. We assume that temperature is the main driver of runoff efficiency variability in the UCRB, based on the results of Nowak et al. (2012) and Woodhouse et al. (2016), however, since we are only considering cool season precipitation, we acknowledge that other climatic factors such as late spring and summer precipitation could influence runoff efficiency as we have defined it. In addition, a relationship remains between precipitation and runoff efficiency due to the many indirect pathways by which precipitation can be connected to runoff efficiency. These can include factors related to soil moisture or base flows that at times influence runoff efficiency (e.g., Miller et al., 2014; Wang et al., 2015; Woodhouse et al., 2016) and are not considered here.

The second reason for basing runoff efficiency on cool season precipitation has to do with the skill that can be expected from the tree-ring data in developing a precipitation reconstruction that is as independent as possible from water year streamflow. Instrumental streamflow and cool season precipitation are not independent due to the hydrologic relationship between those two variables. Consequently, and for related reasons, the reconstructions of streamflow and precipitation will not be independent either. However, the tree-ring chronologies used for the precipitation reconstruction that was specifically developed for this study are independent from chronologies used in the streamflow reconstruction. While most of the tree-ring chronologies in the UCRB region are sensitive to moisture variability for some set of months between the previous October and June of the year of growth, the climate sensitivity "window" to which individual chronologies respond varies. The monthly growth response to climate in the UCRB is most strongly related to tree species, but also can be due to specific site characteristics (e.g., substrate, soil depth, slope angle, elevation). The chronologies screened for the precipitation reconstruction were those that were most strongly correlated with the months of prior October through April moisture, a different set than were selected for the streamflow reconstruction. While there is certainly an overlap in the hydroclimatic information in the trees for cool season precipitation and water year streamflow, more independence is preserved than if we had produced streamflow and precipitation reconstructions for the same water year season. The water year reconstructions would consequently contain enhanced dependence since models would be selected from the same set of tree-ring data.

We hypothesize that the relationships summarized in Table 1 can be applied to reconstructions of annual streamflow and cool season precipitation to evaluate runoff efficiency in the UCRB streamflow over past centuries. Building on these relationships, we use the difference between cool season precipitation and water year streamflow reconstructions to generate a reconstruction of runoff efficiency. We constrain our interpretation of runoff efficiency to those years in which the difference between the standardized cool season precipitation and water year streamflow exceeds one standard deviation for two reasons. First, we are interested in capturing the years in which flow is most strongly influenced by runoff efficiency. Our analyses with instrumental data show that the importance of temperature in runoff efficiency is most robust in years with the greatest difference between flow and precipitation, an aspect we are interested in exploring in the reconstructions. Second, although the reconstructions of precipitation and streamflow are skillful (details below), interpreting small differences between the two series is likely to be within the noise level of the reconstructions. Consequently, the runoff efficiency reconstruction information is most robust for years in which there is a relatively large difference between flow and precipitation. This approach, although conservative, still enables an examination of runoff efficiency as it relates to droughts and pluvials in the streamflow record, the major focus of this research.

3. Data and Methods

3.1. Streamflow, Precipitation, and Temperature Reconstructions

The UCRB and surrounding areas contain a network of existing tree-ring chronologies from trees with growth that is moisture-limited and highly sensitively to hydroclimatic variability (e.g., Schulman, 1956; Woodhouse & Lukas, 2006). These chronologies have been used to generate highly skillful reconstructions of streamflow (e.g., Hidalgo et al., 2000; Meko et al., 2007; Stockton & Jacoby, 1976; Woodhouse et al., 2006) largely because the annual growth of these trees is strongly correlated with cool season moisture (e.g., Meko et al., 1995). Cool season moisture in the form of snowpack in the UCRB has also been reconstructed with a high degree of skill (Pederson et al., 2011; Woodhouse, 2003). The approach applied here, evaluating the difference between reconstructed water year streamflow and cool season precipitation to develop a reconstruction of runoff efficiency, relies on the ability of these trees to replicate both cool season precipitation and water year streamflow variability in the instrumental records.

For streamflow, we used the reconstruction of the Colorado at Lees Ferry from Woodhouse et al. (2006) that covers years 1490–1997. The Lees B version of the streamflow reconstructions was selected because it is characterized by low-order autocorrelation similar to that in the naturalized flow record for the Colorado River at Lees Ferry (approximately $r^1 = 0.25$). The Lees B reconstruction model explains 84% of the variance in the gage record. Since no reconstruction of cool season precipitation exists, we generated a reconstruction using a process similar to that used for the flow reconstruction, but removing chronologies as potential predictors if they had been predictors in the Lees Ferry streamflow reconstruction model, and using the residual version of the chronologies to replicate the lack of autocorrelation in the October–April precipitation time series. The precipitation data used for calibrating the reconstruction are the PRISM (Daly et al., 2008) 4 km resolution grid points for the upper Colorado River basin above Lees Ferry (supporting information Text S2 and Figure S5). All other tree-ring chronologies available that ended in 1999 or later, and correlated significantly ($p \leq 0.05$) with UCRB total October–April precipitation over the common interval, 1906–1999, for the full period and two halves of this period, were retained (25 chronologies). Stepwise regression yielded a model with four predictors, explaining 70% of the variance and spanned 1569–1999 (Figure 1). Model residuals met the assumptions of the multiple linear regression approach. Cross-validation of the model was performed using traditional split sample methods, and both a leave-one-out and a k-folds leave-10-out method replicated 100 times. Additional details on the methodology, tree-ring predictors, and cool season precipitation reconstruction are provided in the supporting information (Text S2, Tables S2 and S3, Figure S6, and Data S1 [Alfons, 2012; Cook et al., 1990; Guentchev et al., 2005]). The correlation between the Lees Ferry streamflow and UCRB cool season precipitation reconstructions over the years 1906–1997 is $r = 0.825$ ($p \leq 0.05$), while correlation between the two instrumental data records for the same period is $r = 0.820$ ($p \leq 0.05$).

Because runoff season (March–July) temperature is a critical control on runoff efficiency (Woodhouse et al., 2016), we were interested in comparing reconstructions of runoff efficiency and temperature for the runoff season. As a close association is expected, a comparison could serve as an independent validation of the reconstruction-based runoff efficiency, though we acknowledge that temperature may not always be the dominant control on runoff efficiency. While temperature reconstructions for the general region (Salzer & Kipfmueller, 2005), or as part of a gridded network do exist (e.g., Wahl & Smerdon, 2012), we have elected not to use these for our comparison since (1) they are not specifically for the UCRB (i.e., they are either too localized, or the gridded networks also integrate tree-ring information located substantial distances away from the basin), (2) may contain tree-ring data used in our precipitation or streamflow reconstructions, (3) do not contain data that extend as far back in time or up to the present as is currently possible, or (4) are seasonal or annual measures of temperature that may not accurately reflect the important runoff season temperatures (see supporting information Figures S8 and S9). To address these potential issues, we develop a new reconstruction of May–July average temperature (henceforth, "late runoff season") for the UCRB using existing tree-ring data, and state-of-the art methods (see supporting information Text S3 and Melvin & Briffa, 2008) designed to enhance the retention of low-frequency climate variability in tree-ring records that may be absent in previous reconstructions. Importantly, though the new temperature reconstruction is specific to the UCRB, since it uses relatively local chronologies (Figure 1), the record still lacks robust information on the key spring months of March and April. Though the chronologies used in the reconstruction exhibit weak correlations to these months, the sign and significance of the relationship can be inconsistent. So, we interpret the reconstruction to be representative of the important late runoff season temperatures while noting some early runoff season information likely carries over into the reconstructed values.

The independent reconstruction of UCRB May–July average temperature was produced as follows: Potential predictor chronologies for use in the reconstruction were selected by acquiring all publicly (ITRDB, 2016; PAGES2k Consortium, 2017) available ring-width and maximum density records that fell within 100 km of the UCRB ($n = 23$, Figure 1, and supporting information Data S1) that exhibited a positive and significant ($p \leq 0.1$) correlation with observed May–July average temperature. The temperature data used for screening and calibrating the reconstruction are the PRISM (Daly et al., 2008) 4 km resolution grid points for the upper Colorado River basin above Lees Ferry. The PRISM temperature data were compared against climate division data (nClimDiv data set, version 2, see Vose et al., 2014) for the UCRB (Divisions: Colorado #2, Wyoming #3, and Utah #6 & 7) to ensure integrity of 20th century trends and variance (supporting information Figure S5). The final May–July average temperature reconstruction was produced by nesting (forward and backward) successively longer, but statistically weaker, best-fit multiple linear regression models through time. As with the precipitation reconstruction, models were cross-validated using traditional split sample methods, and both a leave-one-out and a k-folds leave-10-out method that was replicated 100 times. Reconstruction skill ranges from R^2adj of 0.516–0.217, with cross-validation statistics from the leave-one-out and leave-10-out method equivalent showing the average root mean squared validation error ($RMSE_v$) ranging from 0.581 to 0.643°C (supporting information Figure S7 and Table S2). The nested reconstruction spans the years 1457–1993. A more detailed discussion on these methods along with supporting data and figures can be found in the supporting information (Text S3, Figure S7, Tables S2 and S3, and Data S1; Briffa & Melvin, 2011; Bunn, 2008, 2010; Bunn et al., 2015; Cook et al., 2004, 2014; Lumley & Miller, 2009; Melvin & Briffa, 2008; Melvin et al., 2007; R Core Team, 2013) and online from the USGS (https://doi.org/10.5066/F79885ZT).

3.2. Using Reconstructed Streamflow and Precipitation to Generate an Estimate of Runoff Efficiency

The proxy record for runoff efficiency is based on the difference between the reconstructions of streamflow and cool season precipitation, and thus it is important to assess not only the skill of the individual reconstructions, but the relationships between these two variables. The two reconstructions were standardized and cool season precipitation was subtracted from water year flow to generate a difference series representing runoff efficiency. The correlation between the reconstructed runoff efficiency and streamflow is very similar to the observed runoff efficiency and streamflow correlation, as well as the correlations between runoff efficiency and cool season precipitation (Table 2; correlations based on ratio-based runoff efficiency are in supporting information Table S1). The observed and reconstructed runoff efficiency series track each other fairly closely ($r = 0.53$, $p \leq 0.05$, Figure 2, top). As explained above, we analyze the years with a difference greater than one standard deviation from the mean difference, over the full reconstruction period, 1569–1997 ($n = 134$). In the analyses and discussion that follow, we refer to the years with the largest differences (based on standard deviation) as "anomaly" years.

The anomaly years were analyzed in order to document runoff efficiency over the past four centuries. As in the instrumental data analysis of Woodhouse et al. (2016), the anomaly years were divided into four categories. These years were first divided into years when the standardized annual streamflow was greater (+ runoff efficiency) or less (− runoff efficiency) than the standardized cool season precipitation. The two categories were further subdivided into above and below average streamflow years. The interpretation of the flow, hydroclimatic conditions, and runoff efficiency was based on instrumental data analysis (Woodhouse et al., 2016) (Table 1). The distribution of these four categories of years was examined over the full

Table 2

Correlations Between Water Year Streamflow, October–April Total Precipitation, March–July (Observed) or May–July (Reconstructed) Mean Temperature, and Runoff Efficiency (Water Year Flow−October–April Precipitation), for the Common Time Period, 1906–1993

	Water year streamflow	Oct–Apr total precipitation	Mar (May)–Jul mean temperature[a]	Runoff efficiency
Observations				
Water year streamflow	1.000			
Oct–Apr precipitation	0.817	1.000		
Mar–Jul temperature	−0.180	0.043	1.000	
Runoff efficiency	0.291	−0.314	−0.367	1.000
Reconstruction				
Water year streamflow	1.000			
Oct–Apr precipitation	0.839	1.000		
May–Jul temperature	−0.231	−0.204	1.000	
Runoff efficiency	0.257	−0.310	−0.040	1.000

[a]The residual temperature is used for the observed data, as in Nowak et al. (2012) (controlling for October–April precipitation), but not for the reconstructed temperature since May–July temperature is uncorrelated with reconstructed October–April precipitation.

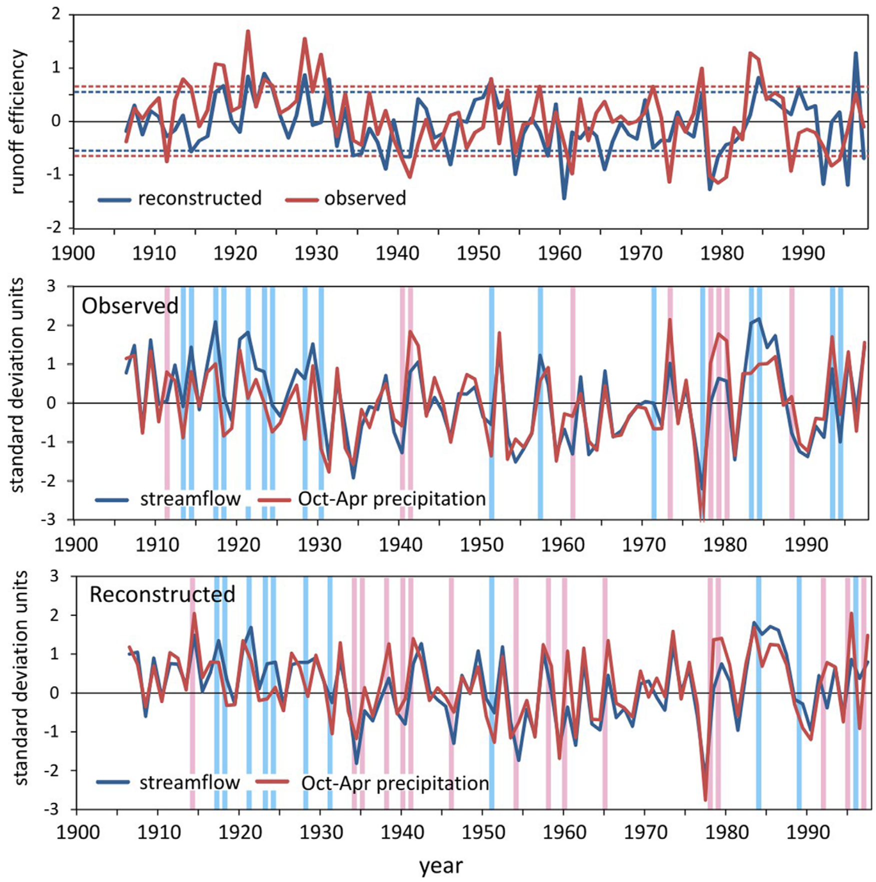

Figure 2. (top) Comparison of time series of runoff efficiency for observed (red) and reconstructed (blue) data, 1906–1997. Runoff efficiency is based on the difference between standardized water year streamflow and cool season precipitation. The dashed horizontal lines indicate difference values one standard deviation from the mean difference, for observed (red) and reconstructed (blue) series. (middle) Observed and (bottom) reconstructed Colorado River water year flow and October–April total precipitation, 1906–1997. Vertical bars are anomaly years: light blue lines indicate positive runoff efficiency years and pink lines indicate negative runoff efficiency years.

period, then summarized over half century periods to facilitate comparison of runoff efficiency during low and high flow years over past centuries.

Next, Colorado River droughts and pluvials were assessed to determine whether some events may have been exacerbated or ameliorated by positive or negative runoff efficiency. Droughts were defined as two or more consecutive years of Colorado River flow below the long-term mean, broken by no more than 1 year of above average flows, and returning to two or more consecutive years below average. Pluvials were defined in a similar way, but based on consecutive above average flow years broken by no more than one below average year, with two or more above average years following. Events of three or more years were considered. Drought events with a relatively high number of negative runoff efficiency years, and pluvials with a relatively high number of positive runoff efficiency years were highlighted.

Finally, a running 20 year average of the runoff efficiency anomaly year values was generated (20 year running counts of positive and negative anomaly years resulted in a very similar result, supporting information Figure S10). This series was then compared to the UCRB May–July temperature reconstruction smoothed with a 20 year cubic spline to assess the correspondence between changes in runoff efficiency and late runoff season temperatures. Our comparison was based on smoothed data because of the uncertainties in the accuracy of annual reconstructed values in both the temperature and runoff efficiency time-series; we have greater confidence in the reconstruction accuracy at decadal and lower frequencies, even though the physical relationships operate on an annual timescale. These series are also compared to the Colorado River streamflow reconstruction to assess flow conditions.

4. Results and Discussion

4.1. Comparison of Anomaly Series in Instrumental and Reconstructed Records

While relationships between runoff efficiency, cool season precipitation, and water year streamflow in the observed and reconstructed data are quite similar, a closer investigation of the reconstructed runoff efficiency is needed to ensure it shares important characteristics with the instrumental runoff efficiency. A close correspondence between the years classified as anomaly years in the observational and reconstructed runoff efficiency depends on relatively small differences ($\leq$ or $\geq 1\ \sigma$ standard deviation) between the runoff and precipitation series. While exact years are not always matched, there is an obvious clustering of positive runoff efficiency years in the 1910s to early 1930s in both records (Figure 2, middle and bottom plots). Negative runoff efficiency years in the reconstruction are more prevalent in the 1930s than in the instrumental data, but overall, key years are matched in both records, as is the general pattern of low-frequency variability (Figure 2, top plot).

When the relative proportion of years that fall into the four categories of runoff efficiency years (positive and negative runoff efficiency, with above and below average flows, Table 1) is compared, along with the runoff efficiency, water year flow, and cool season precipitation values, the observed and reconstructed records show very similar results (Figures 3a and 3b). The largest difference is evident within the category of negative efficiency years; with slightly greater runoff efficiencies shown in the reconstructed data relative to the observed data in both high and low flow years. Additionally, the negative efficiency, low flow years in the reconstructed data are slightly more numerous, showing several lower estimates of flow and precipitation than in the observed record. This particular pattern of difference could introduce a possible bias in the full-length reconstruction toward slightly more negative runoff efficiency years with higher estimated runoff

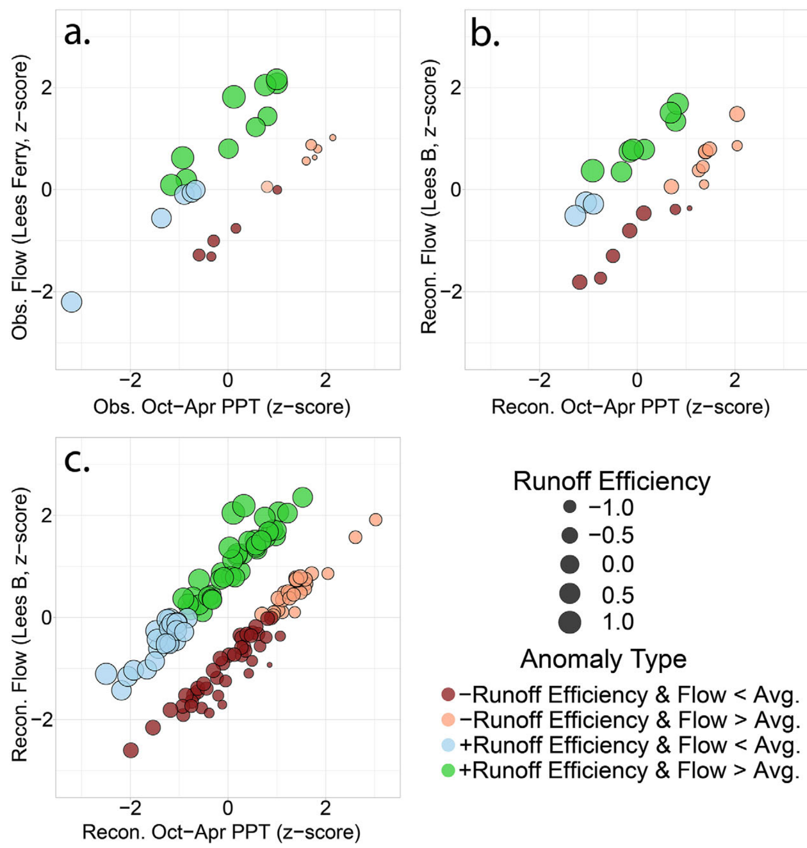

Figure 3. Classified runoff efficiency anomaly years (flow-P $\leq -1\ \sigma$ or $\geq 1\ \sigma$) for: (a) observed data, 1906–1997; (b) reconstructions, 1906–1997; and (c) the full reconstructions, 1569–1997. The scatterplots show the four categories of anomaly years relative to Colorado River water year flow and total cool season precipitation (October–April), with the dot size relative to the inferred runoff efficiency. Large dots (positive values) represent high runoff efficiency, and small dots (negative values) show low runoff efficiency years in each category.

efficiencies than actually occurred. Overall, these comparisons provide support for the difference approach using the reconstructions to produce runoff efficiency similar to that produced using the instrumental data, and in particular, for years when differences between reconstructed flow and precipitation are greatest. In addition, the proportion of these four types of runoff efficiency years, and the relative values for runoff efficiency, water year flow, and cool season precipitation by category, are quite similar when assessed over the full reconstruction period (Figure 3c). Not surprisingly, the full reconstruction provides more examples of extreme conditions in each anomaly type, with the most common types of years classified as either positive runoff efficiency and high flows, or negative efficiency and low flows.

4.2. Temporal Patterns of UCRB Runoff Efficiency

The distribution of the four categories of runoff efficiency years over the full record, 1569–1997, indicates times in which runoff efficiency, likely related to runoff season temperature, modulated the effects of cool season precipitation on annual streamflow, and times when flows more closely matched to cool season precipitation (i.e., nonanomaly years; Figure 4b). The early part of the 1600s and the 1830–1840s stand out as periods when flows were higher than average, with positive runoff efficiency. These conditions are evident in nearly half of the years in the 15 year period from 1605 to 1619, and in six of 10 years in the period from 1835 to 1844. Years with lower flows and negative runoff efficiency are less clustered, but 3 year sequences occur in the 1780s and 1890s, indicating sets of years when warm runoff season temperatures maybe have further reduced already low flows. Lower flow years with positive runoff efficiency are irregularly distributed throughout the four centuries, suggesting that years with cooler temperatures alleviating low flows are not characteristic of any particular period of time. However, a number of these years occur within or near sequences of high flow, positive runoff efficiency years suggesting a persistence of cool conditions even under low flows. Years with higher than average flows and negative runoff efficiency are most prevalent in the 20th century. In these years, warmer runoff season temperatures may be reducing the effectiveness of precipitation's contribution to streamflow. The longest intervals of time when flows are more closely matched by cool season precipitation (e.g., few extreme values of runoff efficiency) are four 12 year periods, two occurring in the 17th and two in 20th century. Two of these periods were characterized by generally high flows (1690–1701, 1906–1917), but in the other two, flows were more variable.

The frequency of these four categories of years over half-century periods provides a summary of the variability of runoff efficiency over time. Above average flows with positive runoff efficiency occurred most often in the first halves of the 17th and 18th centuries, but much less frequently in the half century between these two periods (Figure 5a). The first half of the 18th century had the largest proportion of positive runoff efficiency years (almost a quarter of the years), regardless of level of flow. However, this period also had an almost equal number of years that indicate negative runoff efficiency (Figure 5b). Together, this suggests the first half of the 18th century was a period of highly variable climate, and likely with respect to both temperature and streamflow. In contrast, the first half of the 19th century had the highest proportion of years with positive runoff efficiency compared to those with negative runoff efficiency (11 versus 7 years), suggesting it may have been the coolest interval of time, with respect to the runoff season. In support of this, the early 19th century is widely documented to be one of the coolest periods across western North America in the last 1,000 years (Trouet et al., 2013; Wahl & Smerdon, 2012), a finding that is further supported by the UCRB late runoff season temperature reconstruction (Figure 6b and supporting information Figure S7).

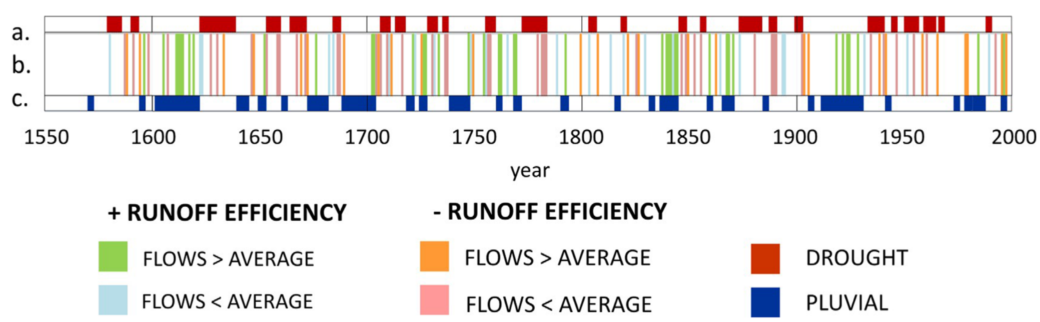

Figure 4. Distribution of (a) Colorado River droughts, (b) anomaly years in the four runoff efficiency/flow categories, and (c) Colorado River pluvials, 1569–1997.

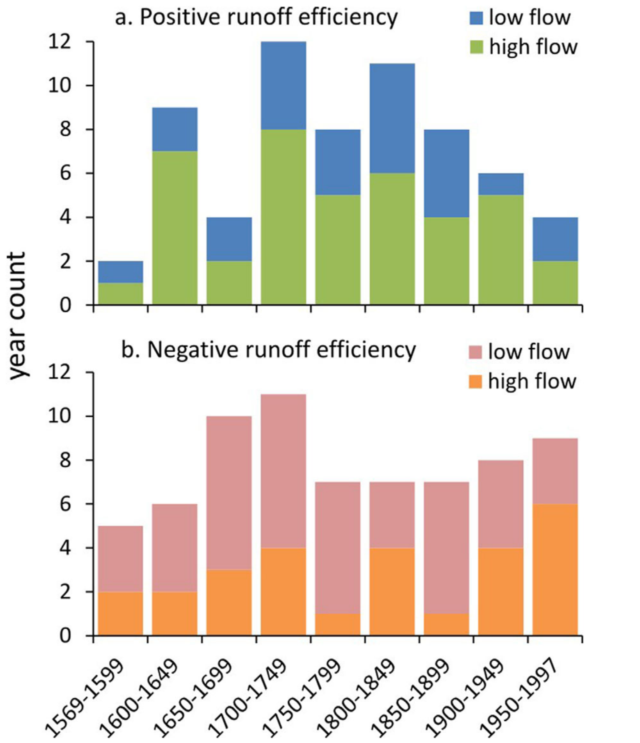

Figure 5. The number of years in each category shown by half-century periods (first period has 31 years; the last has 48 years) for (a) positive runoff efficiency years and (b) negative runoff efficiency years.

Years with below average flows and negative runoff efficiency occurred most frequently in second half of the 17th century and first half of the 18th century. These dry and likely warm years are interspersed with wetter, positive runoff efficiency years in the first half of the 18th century (Figure 5b), but the prior half-century had the fewest occurrences of years with positive runoff efficiency of any half-century period (although matching the last half of the 20th century, which contains only 48 years). The distribution of above average flow years with negative runoff efficiency was greatest in the 20th century ($n = 10$ years), with at least twice as many occurrences as in any other century.

4.3. Runoff Efficiency Impacts on Drought and Pluvials Over the Past 400 Years

Analyses of the occurrence of runoff efficiency anomaly years, in conjunction with periods of drought and pluvial conditions, provide insights on how runoff efficiency may either exacerbate or ameliorate Colorado River flow conditions. Runs of consecutive below average flow years, broken by no more than a single year, range in length from 3 to 12 years (Figure 4a). Although most drought years occur with low flows tracking precipitation deficits (i.e., nonanomaly years), several droughts stand out for the relatively high occurrence of years when runoff efficiency is especially negative and thus when temperature may be more influential. Specifically, three periods of drought were notable for a higher proportion of years with negative runoff efficiency. These were 1653–1659 (three of 7 years), 1772–1783 (four of 12 years), and 1887–1890 (three of 4 years). Precipitation deficits were modest over these years compared to flow deficits (Table 3), suggesting the more extreme streamflow deficits, relative to precipitation, may be a result of warm runoff season temperatures.

Two long periods of drought of similar length but differing flow deficits were 1772–1782 (12 years) and 1873–1883 (11 years; Table 3). Although there may have been a variety of reasons for the differences in streamflow for these two droughts, the occurrence of four negative runoff efficiency years at the end of the 1700s drought may have resulted in greater deficits in flow during this drought. In contrast, the 1800s drought had greater precipitation deficits, with just 1 year with a negative runoff efficiency anomaly, and 2 years at the onset of the drought with positive runoff efficiency, in which cooler temperatures may have reduced the impact of precipitation deficits.

Persistent pluvials in Colorado River streamflow were evident in the early 1600s and in the early 1900s (Figure 4c). These coincided with a number of years with positive runoff efficiency anomalies (seven of 21 years from 1601 to 1621 and five of 20 years from 1911 to 1930). Annually averaged, the standardized flows were higher over these two periods relative to the standardized precipitation, although this is less marked in the 20th century pluvial (Table 3). These two pluvials, plus two others, 1836–1844 and 1865–1870, were the events with the highest number of positive runoff anomaly years. In the period 1836–1844, six of 9 years were positive runoff efficiency years, and in 1865–1870, this occurred in three of 6 years. The two 19th century pluvials had the highest annual average flows of any pluvial period, and with a high proportion of positive runoff efficiency years, the high flows may have, at least in part, been a result of cooler runoff season temperatures.

4.4. Evaluating Runoff Efficiency in the Context of Temperature Variability

The 20 year running average of the runoff efficiency anomaly years (Figure 6a) documents decadal periods when cool season precipitation was more or less efficient with regard to its contribution to streamflow. The running average of anomaly year values is plotted with a bar plot showing all runoff efficiency values to indicate that the anomaly years are generally representative of the full series at this timescale (Figure 6a). While it is likely that the positive runoff efficiency periods reflect cooler conditions, and the negative runoff

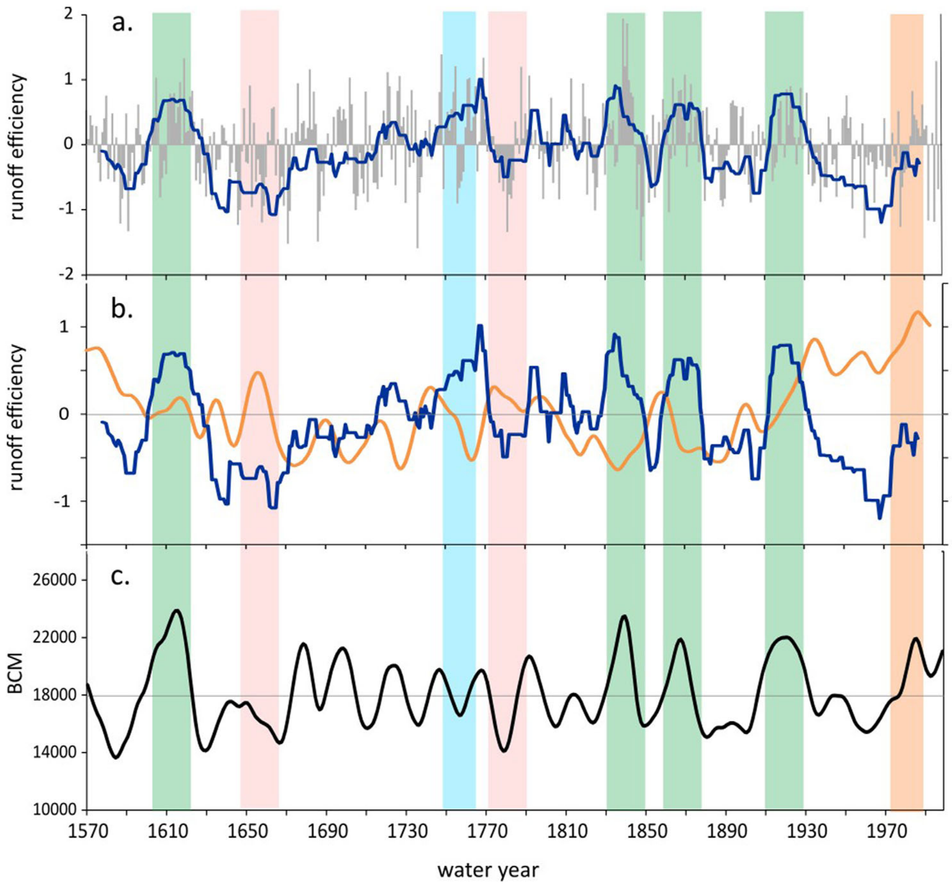

Figure 6. (a) Runoff efficiency, annual values (gray bars) with 20 year running mean of runoff efficiency values for anomaly years only (dark blue line) plotted on middle year; (b) 20 year running mean of runoff efficiency for anomaly years (dark blue line) with the late runoff season May–June temperature reconstruction, smoothed with a 20 year spline (orange line); (c) Colorado River at Lees Ferry water year streamflow shown in billion cubic meters (smoothed with a 20 year spline). Vertical shaded bars are examples of the four categories of runoff efficiency years: negative efficiency, low flows (pink); negative efficiency, high flows (orange); positive efficiency, high flows (green); positive efficiency, low flows (blue).

efficiency periods reflect warmer temperatures, there are some challenges associated with confirming this relationship. As mentioned above, the reconstruction of late runoff season temperature is only for a portion of the season that is most closely linked to water year streamflow (May–July instead of March–July). In addition, the correlation between reconstructed runoff season temperature and reconstructed runoff efficiency is near zero for the instrumental period, in comparison to the correlation for the instrumental data, $r = -0.367$ (with residual temperature; the residual temperature is not used with the reconstruction since reconstructed temperature and precipitation are not significantly correlated) (Table 2). By smoothing the series, we instead assess the tendency for coherence at decadal and greater timescales between runoff efficiency and temperature.

Table 3
Selected Drought and Pluvial Period Average Annual Values Over Years of the Event in Standard Deviation Units

Years of drought or pluvial (# of years)	Runoff efficiency	Water year flow	Cool season precipitation
Droughts			
1653–1659 (7)	−0.573	−0.652	−0.079
1772–1783 (12)	−0.396	−0.796	−0.399
1873–1883 (11)	0.197	−0.547	−0.744
1887–1890 (4)	−0.766	−0.920	−0.154
Pluvials			
1601–1621 (21)	0.322	0.892	0.570
1836–1844 (9)	0.950	1.343	0.395
1865–1870 (6)	0.592	1.179	0.587
1911–1930 (20)	0.149	0.637	0.488

A comparison of the smoothed time series of late runoff season temperature with the runoff efficiency series does suggest correspondence between temperature, water year streamflow, and runoff efficiency over decadal time periods (Figures 6b and 6c). A general expectation, based on prior work (e.g., Lehner et al., 2017; Woodhouse et al., 2016), is that cool temperatures coincide with positive runoff efficiency and warm temperatures with negative runoff efficiency, and

Figure 6b indicates that this is generally, although not always, the case. A close correspondence between flow and runoff efficiency, also expected, is documented (Figure 6c).

Two of the three droughts listed in Table 3 with negative runoff efficiency (1650s, 1770s) appear to have been accompanied by warm temperatures (Figure 6b, pink vertical bars). The third, in the late 1880s and only 4 years in duration, may be too short for this comparison. Of the pluvials, the two occurring in the 19th century (Table 3) clearly coincided with cooler temperatures and positive runoff efficiency. The early 1600s pluvial occurred under near average conditions, while the early 20th century pluvial started under cool conditions which warmed over the pluvial period (Figure 6b, green vertical bars).

The two other types of conditions, low flows with positive runoff efficiency, and high flows with negative runoff efficiency are documented as well, but they are uncommon. In 1750s, flows are somewhat below average, while runoff efficiency is quite high, and temperatures are cool, in agreement with low flows being mitigated by cooler temperatures (Figure 6b, blue vertical bar). There is no other period of time with this set of characteristics, but individual years, although rare, are documented (Figure 4b). The 1950s drought, which seemed to fall into this category in the instrumental data (Woodhouse et al., 2016), is not evident in this context. The most notable period with relatively high flow, but negative runoff efficiency is at the end of the 20th century (Figure 6b, orange vertical bar), in agreement with Figure 5b. Runoff season temperature was the warmest on record over this interval, suggesting the high temperatures drove low runoff efficiency, resulting in flows that might have been higher under cooler temperatures.

5. Conclusions

Insights on the role of runoff efficiency on Colorado River streamflow over the past four centuries can be obtained from the difference between reconstructed cool season precipitation and annual streamflow. In the UCRB, this approach is possible because of the network of highly moisture sensitive tree-ring chronologies that have allowed the development of complementary reconstructions of both cool season precipitation and water year streamflow from mutually exclusive sets of predictor chronologies. As expected, flow and precipitation are highly correlated in both the reconstructed and observed time series. However, analyses of the observed and reconstructed hydroclimatic variables and the derived estimate of runoff efficiency show similar relationships with respect to flow and precipitation over the common time period, supporting the ability of the reconstructions to replicate runoff efficiency with some accuracy. Based on instrumental data analysis, the most robust information concerning the role of temperature is contained in the years with the largest difference between flow and precipitation, so we focused on those "anomaly" years in the analysis of the reconstructions. When assessed in terms of four categories of anomaly years, the reconstructions replicated well the proportion of years in the four categories in the instrumental data, as well as the relationships between flow and precipitation in each of the four sets of years.

Multiyear to decadal-scale periods of drought in Colorado River streamflow are a well-established feature of this semiarid watershed (Meko et al., 1995; Nowak et al., 2012; Woodhouse et al., 2006). Results here suggest that over the past four centuries, runoff efficiency, primarily driven by temperatures, has likely played a role in exacerbating the impacts of precipitation deficits on low flows. On a relatively regular basis, persistent droughts contain years with runoff temperatures warm enough to further intensify low flows beyond what would be expected from precipitation deficits alone. The 20th century does not appear unusual in this regard (at least prior to 1997), although instrumental data analysis extending into the 21st century does suggest a higher frequency of low flow years exacerbated by warm runoff season temperatures in recent decades (Udall & Overpeck, 2017; Woodhouse et al., 2016).

While there are fewer years that suggest positive runoff efficiency with cool conditions that ameliorate precipitation deficits on streamflow, they do occur. Except for a period in the 1750s, these years are generally not a characteristic of particular droughts, but individually occur most often during relatively cooler intervals of time, such as the 19th century. Consequently, precipitation deficits during these intervals may have had more moderate impacts on streamflow, relative to droughts that occurred during warmer periods. Although relatively rare, and likely to become increasingly so as temperatures trend warmer over coming decades, these years have continued to occur through the 20th century. Given their moderating influence on low flows, anticipating the impacts of these types of years could be useful for water management. The recent temporary "slowdown" in surface temperature warming is an indication that warming trends include imbedded temperature variability (e.g., Mann et al., 2016; Meehl et al., 2014; Trenberth et al., 2014). Taking into consideration the covariability of cooler temperatures (even in relative terms) in association with below average precipitation could provide some additional insights that allow water managers to capitalize on these rare years—in addition to being better prepared for more acute flow reductions during warm years.

The record of past pluvials appears to coincide well with positive runoff efficiency and cooler temperatures, particularly in the 19th century. The most recent persistent pluvial, in the beginning of the 20th century occurred under positive runoff efficiency conditions, but also under a trend of warming temperatures. During this time period, high spring precipitation, documented as a characteristic of the pluvial (Woodhouse et al., 2005), may have contributed to the higher runoff efficiency, along with temperatures. Periods with higher flows, but under lower runoff efficiency appear to be occurring with increasing frequency over the later part of the 20th century, documented in both instrumental data (e.g., Woodhouse et al., 2016) and in the longer paleoclimatic records here.

Results presented here indicate that temperature-modulated runoff efficiency has been a consistent influence in the UCRB over the past four centuries, influencing streamflow in both positive and negative ways. Because of the relationship between temperature and runoff efficiency, there are clear implications for the impact of warming temperature on water supplies. Recent work has shown that temperatures are having an increasing influence on snow-fed water resources (e.g., Pederson et al., 2013; Scalzitti et al., 2016), and a strong manifestation of that is a reduced runoff efficiency, documented in recent decades, and likely to increase with a warmer future. Furthermore, the results here suggest that by incorporating the influence of runoff season temperatures on runoff efficiency, the accuracy of seasonal water supply forecasts for the UCRB (and likely other basins) could be improved, enhancing water management, and drought planning efforts.

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References

Alfons, A. (2012). *cvTools: Cross-validation tools for regression models* (R package ver. 0.3.2). Retrieved from http://CRAN.R-project.org/package=cvTools

Briffa, K. R., & Melvin, T. M. (2011). A closer look at regional curve standardization of tree-ring records: Justification of the need, a warning of some pitfalls, and suggested improvements in its application. In M. K. Hughes et al. (Eds.), *Dendroclimatology* (Vol. 11, pp. 113–145). Dordrecht, the Netherlands: Springer.

Bunn, A. G. (2008). A dendrochronology program library in R (dplR). *Dendrochronologia*, *26*(2), 115–124. https://doi.org/10.1016/j.dendro.2008.01.002

Bunn, A. G. (2010). Statistical and visual crossdating in R using the dplR library. *Dendrochronologia*, *28*(4), 251–258. https://doi.org/10.1016/j.dendro.2009.12.001

Bunn, A. G., Korpela, M., Biondi, F., Campelo, F., Mérian, P., Qeadan, F., & Zang, C. (2015). *dplR: Dendrochronology program library* (R. R package ver. 1.6.2). Retrieved from http://CRAN.R-project.org/package=dplR

Cook, E. R., Briffa, K., Shiyatov, S. G., & Mazepa, S. V., & (1990). Tree-ring standardization and grow-trend estimation. In E. R. Cook & L. Kairiukstis (Eds.), *Methods of dendrochronology: Applications in the environmental sciences* (pp. 104–123). Dordrecht, the Netherlands: Kluwer Academic/Springer.

Cook, E. R., Krusic, P. J., & Melvin, T. (2014). *RCS signal free program: Version 45 (2b)*. Palisades, NY: Tree-Ring Laboratory, Lamont-Doherty Earth Observatory (compiled on 16 March 2014).

Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., & Stahle, D. W. (2004). Long-term aridity changes in the Western United States. *Science*, *306*(5), 1015–1018. https://doi.org/10.1126/science.1102586

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., . . . Pasteris, P. P. (2008). Physiographically-sensitive mapping of temperature and precipitation across the conterminous United States. *International Journal of Climatology*, *1*, 2031–2064.

Frans, C., Istanbulluoglu, E., Mishra, V., Munoz-Arriola, F., & Lettenmaier, D. P. (2013). Are climatic or land cover changes the dominant cause of runoff trends in the upper Mississippi River basin? *Geophysical Research Letters*, *40*, 1104–1110. https://doi.org/10.1002/grl.50262

George, S. S. (2014). An overview of tree-ring width records across the Northern hemisphere. *Quaternary Science Reviews*, *95*, 132–150. https://doi.org/10.1016/j.quascirev.2014.04.029

Guentchev, G., Barsugli, J. J., & Eischeid, J. (2005). Homogeneity of gridded precipitation data sets for the Colorado River basin. *Journal of Applied Meteorology and Climatology*, *46*, 2404–2415. https://doi.org/10.1175/2010JAMC2484.1

Gupta, S. C., Kessler, A. C., Brown, M. K., & Zvomuya, F. (2015). Climate and agricultural land use change impacts on streamflow in the upper Midwestern United States. *Water Resources Research*, *51*, 5301–5317. https://doi.org/10.1002/2015WR017323

Hidalgo, H. G., Piechota, T. C., & Dracup, J. A. (2000). Alternative principal components regression procedures for dendrohydrologic reconstructions. *Water Resources Research*, *36*, 3241–3249. https://doi.org/10.1029/2000WR900097

ITRDB (2016). National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce. Retrieved from https://data.noaa.gov/dataset/international-tree-ring-data-bank-itrdb

Lehner, F., Wahl, E. R., Wood, A. W., Blatchford, D. B., & Llewellyn, D. (2017). Assessing recent declines in Upper Rio Grande River runoff efficiency from a paleoclimate perspective. *Geophysical Research Letters*, *44*, 4124–4133. https://doi.org/10.1002/2017GL073253

Lumley, T., & Miller, A. (2009). *Leaps: Regression subset selection* (R package ver. 2.9, using Fortran code by A. Miller). Retrieved from http://CRAN.R-project.org/package=leaps

Mann, M. E., Steinman, B. A., Miller, S. K., Frankcombe, L. M., England, M. H., & Cheung, A. H. (2016). Predictability of the recent slowdown and subsequent recovery of large-scale surface warming using statistical methods. *Geophysical Research Letters*, *43*, 3459–3467. https://doi.org/10.1002/2016GL068159

McCabe, G. J., & Wolock, D. M. (2016). Variability and trends in runoff efficiency in the conterminous United States. *Journal of the American Water Resources Association*, *52*, 1046–1055. https://doi.org/10.1111/1752-1688.12431

Meehl, G. A., Teng, H., & Arblaster, J. M. (2014). Climate model simulations of the observed early-2000s hiatus of global warming. *Nature Climate Change*, *4*(10), 898–902. https://doi.org/10.1038/nclimate2357

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

Meko, D. M., Woodhouse, C. A., Baisan, C. A., Knight, T., Lukas, J. J., Hughes, M. K., & Salzer, M. W. (2007). Medieval drought in the upper Colorado River Basin. *Geophysical Research Letters*, *34*, L10705. https://doi.org/10.1029/2007GL029988

Melvin, T., & Briffa, K. (2008). A ''signal-free'' approach to dendroclimatic standardisation. *Dendrochronologia*, *26*(2), 71–86. https://doi.org/10.1016/j.dendro.2007.12.001

Melvin, T., Briffa, K., Nicolussi, K., & Grabner, M. (2007). Time-varying-response smoothing. *Dendrochronologia*, *25*(1), 65–69.

Miller, M. P., Susong, D. D., Shope, C. L., Heilweil, V. M., & Stolp, B. J. (2014). Continuous estimation of baseflow in snowmelt-dominated streams and rivers in the Upper Colorado River Basin: A chemical hydrograph separation approach. *Water Resources Research*, *50*, 6986–6999. https://doi.org/10.1002/2013WR014939

Nowak, K., Hoerling, M., Rajagopalan, B., & Zagona, E. (2012). Colorado River basin hydroclimatic variability. *Journal of Climate*, *25*, 4389–4403. https://doi.org/10.1175/JCLI-D-11-00406.1

PAGES2k Consortium (2017). A global multiproxy database for temperature reconstructions of the Common Era. *Scientific Data*, *4*, 170088. https://doi.org/10.1038/sdata.2017.88

Pederson, G. T., Betancourt, J. L., & McCabe, G. J. (2013). Regional patterns and proximal causes of the recent snowpack decline in the Rocky Mountains, U.S. *Geophysical Research Letters*, *40*, 1811–1816. https://doi.org/10.1002/grl.50424

Pederson, G. T., Gray, S. T., Woodhouse, C. A., Betancourt, J. L., Fagre, D. B., Littell, J. S., . . . Graumlich, L. J. (2011). The unusual nature of recent snowpack declines in the North American cordillera. *Science*, *333*, 332–335. https://doi.org/10.1126/science.1201570

R Core Team (2013). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Salzer, M. W., & Kipfmueller, K. F. (2005). Reconstructed temperature and precipitation on a millennial timescale from tree-rings in the southern Colorado Plateau. *Climatic Change*, *70*, 465–487. https://doi.org/10.1007/s10584-005-5922-3

Scalzitti, J., Strong, C., & Kochanski, A. (2016). Climate change impact on the roles of temperature and precipitation in western U.S. snowpack variability. *Geophysical Research Letters*, *43*, 5361–5369. https://doi.org/10.1002/2016GL068798

Schulman, E. (1956). *Dendroclimatic changes in semiarid America*. Tucson, AZ: University of Arizona Press.

Stockton, C. W., & Jacoby, G. C. (1976). Long-term surface-water supply and streamflow trends in the Upper Colorado River Basin. In J. M. Varady et al. (Eds.), *Lake Powell research project bulletin* (Vol. 18). Arlington, VA: National Science Foundation.

Trenberth, K. E., Fasullo, J. T., Brandstator, G., & Phillips, A. S. (2014). Seasonal aspects of the recent pause in surface warming. *Nature Climate Change*, *4*, 911–916. https://doi.org/10.1038/nclimate2341

Trouet, V., Diaz, H. F., Wahl, E. R., Viau, A. E., Graham, R., Graham, N., & Cook, E. R. (2013). A 1500-year reconstruction of annual mean temperature for temperate North America on decadal-to-multidecadal time scales. *Environmental Research Letters*, *8*, 024008–024010. https://doi.org/10.1088/1748-9326/8/2/024008

Udall, B., & Overpeck, J. T. (2017). The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research*, *53*, 2404–2418. https://doi.org/10.1002/2016WR019638

Vose, R. S., Applequist, S., Durre, I., Menne, M. J., Williams, C. N., Fenimore, C., . . . Arndt, D. (2014). Improved historical temperature and precipitation time series for U.S. climate divisions. *Journal of Applied Meteorology and Climatology*, *53*, 1232–1251. https://doi.org/10.1175/JAMC-D-13-0248.1

Wahl, E. R., Diaz, H. F., & Ohlwein, C. (2012). A pollen-based reconstruction of summer temperature in central North America and implications for circulation patterns during medieval times. *Global and Planetary Change*, *84*, 66–74. https://doi.org/10.1016/j.gloplacha.2011.10.005

Wahl, E. R., & Smerdon, J. E. (2012). Comparative performance of paleoclimate field and index reconstructions derived from climate proxies and noise-only predictors. *Geophysical Research Letters*, *39*, L06703. https://doi.org/10.1029/2012GL051086

Wang, H., Sankarasubramanian, A., & Ranjithan, R. S. (2015). Understanding the low-frequency variability in hydroclimatic attributes over the southeastern US. *Journal of Hydrology*, *521*, 170–181.

Woodhouse, C. A. (2003). A 431-year reconstruction of western Colorado snowpack. *Journal of Climate*, *16*, 1551–1561.

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

Woodhouse, C. A., Kunkel, K. E., Easterling, D. R., & Cook E. R. (2005). The twentieth-century pluvial in the western United States. *Geophysical Research Letters*, *32*, L07701. https://doi.org/10.1029/2005GL022413

Woodhouse, C. A., & Lukas, J. J. (2006). Multi-century tree-ring reconstructions of Colorado streamflow for water resource planning. *Climatic Change*, *78*, 293–315. https://doi.org/10.1007/s10584-006-9055-0

Woodhouse, C. A., Pederson, G. T., Morino, K., McAfee, S. A., & McCabe, G. J. (2016). Increasing influence of air temperature on upper Colorado River streamflow. *Geophysical Research Letters*, *43*, 2174–2181. https://doi.org/10.1002/2015GL067613