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Key Points:

- A new tree-ring based ensemble streamflow reconstruction spanning the last two millennia was developed for the Colorado River
- The new reconstruction reveals a second-century drought unmatched in severity by any past droughts in the Upper Colorado River Basin
- The ongoing 22-year period of low Colorado River streamflow is a rare event, but is not the most severe drought in the past 2,000 years

Supporting Information:

Supporting Information may be found in the online version of this article.

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Tree Rings Reveal Unmatched 2nd Century Drought in the Colorado River Basin

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Abstract

The ongoing 22-year drought in the Upper Colorado River Basin (UCRB) has been extremely severe, even in the context of the longest available tree-ring reconstruction of annual flow at Lees Ferry, Arizona, dating back to 762 CE. While many southwestern drought assessments have been limited to the past 1,200 years, longer paleorecords of moisture variability do exist for the UCRB. Here, gridded drought-atlas data in the UCRB domain along with naturalized streamflow data from the instrumental period (1906–2021) are used in a *K*-nearest neighbor nonparametric algorithm to develop a streamflow reconstruction for the Lees Ferry gage starting in 1 CE. The reconstruction reveals a second-century drought unmatched in severity by the current drought or by well-documented medieval period droughts in the UCRB. Although data are sparse, analysis of individual long tree-ring records and other paleoclimatic data also support the occurrence of an exceptional second-century drought.

Plain Language Summary

The Colorado River drought we currently are experiencing is severe in the context of the 116-year gage record (1906–2021), but how severe is it in a long-term context? Existing tree-ring based reconstructions of Colorado River streamflow have suggested that the 22-year period 2000–2021 could be the worst drought in the southwestern United States in 1,200 years. The purpose of this study is to extend the Colorado River reconstruction back 2,000 years and to evaluate the current drought in a long-term context. We find that an even more extreme drought occurred and persisted over much of the second century. Data are sparse this far back in time, but evidence from both tree-ring data and paleoclimate data from lakes, bogs, and caves supports the existence and severity of this drought in the context of the last two millennia. Additional work is needed to learn more about this drought and its causes, but we now know that drought more persistent than even the well-documented medieval period droughts occurred in the past, expanding our understanding of the range of natural climate variability.

1. Introduction

Colorado River drought has persisted since 2000 (when defined as below average flows broken by no more than one year of above average streamflow), with an average annual flow of 15.2 billion cubic meters (bcm) (12.3 million acre-feet (maf)), or 84% of the 1906–2021 mean (Reclamation, 2021a). The significance of this persistent drought was made apparent in August 2021 when the first ever shortage declaration was called by the Bureau of Reclamation in anticipation of reservoir level declines resulting from ongoing drought (Reclamation, 2021b). As of around mid-April 2022, the two largest reservoirs on the Colorado River, Lakes Powell and Mead, are only 24% and 32% full, respectively (Reclamation, 2022). Reduced inflow to reservoirs has been driven by precipitation deficits and exacerbated by increased temperature, which is estimated to account for about one-third of the decrease in Colorado River streamflow measured at the Lees Ferry, Arizona gage (Figure 1) over 2000–2017 (Udall & Overpeck, 2017).

A key question being asked is: how does this current drought compare with those of the past? Is it similar in persistence and severity to past droughts, or does it represent an unprecedented extreme? Streamflow for 2000–2021 is lower than for any other 22-year period in the gaged record, but that record only extends to 1906. The running 22-year observed mean water-year flow at Lees Ferry has now dropped below the lowest 22 years mean (15.6 bcm, or 12.6 maf) in the 762–2005 CE tree-ring reconstruction by Meko et al. (2007), suggesting that

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smoothed annual flows on the Colorado River are now lower than at any other time in the last 12 centuries. This is consistent with recent findings by Williams et al. (2022), who report that 2000–2021 is the driest 22-year period across the southwest United States in the same time frame.

Much of the research addressing the severity of the ongoing drought in the southwest United States relative to that of past droughts has relied upon a set of moisture-limited tree-ring chronologies that has been utilized to develop gridded reconstructions of drought—e.g., North American Drought Atlas (NADA; Cook & Krusic, 2004; E. R. Cook & Krusic, 2004), Living Blended Drought Atlas (LBDA; Cook et al., 2010), seasonal precipitation (Stahle et al., 2020), and soil moisture (Williams et al., 2020, 2022). The numerous spatial analyses that have utilized this tree-ring network (e.g., Coats et al., 2015; Cook et al., 2015; Ho et al., 2016) have been limited to the time period when the network has coverage for large parts of the United States. While both the North American Drought Atlas (NADA) and the Living Blended Drought Atlas (LBDA) contain grid point reconstructions back to 1 CE, the coverage is quite limited until 800 CE, the start date for most studies. The region for which there are grid point reconstructions back to 1 CE includes the Upper Colorado River Basin (UCRB) (Figure 1). Although the tree-ring data are sparse, the Living Blended Drought Atlas (LBDA) for this subregion suggests the potential to extend by seven centuries the longest published Lees Ferry flow reconstruction (762 CE; Meko et al., 2007).

Tree-ring studies that record Southwest drought before 800 CE suggest the occurrence of extreme events that merit further examination. In a 2,300-year reconstruction of precipitation in the northwestern Upper Colorado River Basin (UCRB), Knight et al. (2010) highlight a drought in early 500s as the most severe in 1,800 years. Their reconstruction also shows a notable drought in the second century. Just outside of the Basin, in the Rio Grande headwaters of the San Juan Mountains (also headwaters for the UCRB), a tree-ring proxy record of moisture variability shows a severe drought in the second century that is the driest period in over 2,250 years (Routson et al., 2011). Moreover, Routson et al. (2016) also found evidence for increased dust activity in the second century in proxy records of dustiness from lake sediments in the same region. Further south, a 2,129-year reconstruction of annual precipitation for northwestern New Mexico shows a number of notable droughts in the first millennium, including drought conditions in the mid-third to early sixth centuries, and a particularly persistent drought in the second century (Grissino-Mayer, 1996). To the west, a reconstruction of precipitation for the White Mountains in eastern California from bristlecone pine shows no drought in the second century, but does show a period of sustained drought in the sixth century (Hughes & Graumlich, 1996).

These studies suggest an extended reconstruction of Colorado River streamflow could reveal a broader range of drought conditions than documented by existing reconstructions. Of particular interest is the second century, which falls within an historical climate epoch known as the Roman Warm Period, first identified and characterized by Lamb (1977) as a period of anomalous warm temperatures in Europe, approximately 100 to 400 CE. A number of historical archives and paleoclimate records reflect anomalously warm conditions in locations beyond Europe, including Iceland, the North Atlantic, southwest Florida, and more broadly across the northern hemisphere for intervals of time over the period of 1–500 CE (e.g., Bianchi & McCave, 1999; Lapointe et al., 2020; Ljungqvist, 2010; Patterson et al., 2010; Rodysill et al., 2018; Wang et al., 2013). However, taken together, available data do not support a spatially coherent warm period over this interval of time (Neukom et al., 2019). Similarly, the so-called Medieval Warm Period (~800–1300 CE) was not a spatially coherent period of warmth (Hughes & Diaz, 1994), but did coincide with drier conditions across the southwest United States (e.g., Meko et al., 2007).

In this study, we adapt the nonparametric K-nearest neighbor (KNN) methodology of Gangopadhyay et al. (2009) to utilize existing grid point reconstructions of Palmer Drought Severity Index (PDSI; Palmer, 1965) from the LBDA (Cook et al., 2010; Gille et al., 2017) for the Upper Colorado River Basin (UCRB) to develop a two thousand year reconstruction of Colorado River streamflow at Lees Ferry. We chose to use the grid point reconstructions rather than tree-ring chronologies as basic tree-ring predictors for several reasons. First, the gridded reconstructed Palmer Drought Severity Index (PDSI), which has high accuracy and skill in the UCRB, incorporates tree-ring chronologies screened for moisture sensitivity and filtered to account for lag in tree-growth response to climate (Cook et al., 2007). In addition, the gridded reconstructions provide a uniform spatial and temporal resolution of drought data advantageous to the application of the K-nearest neighbor (KNN) approach in streamflow reconstruction for the Colorado River.

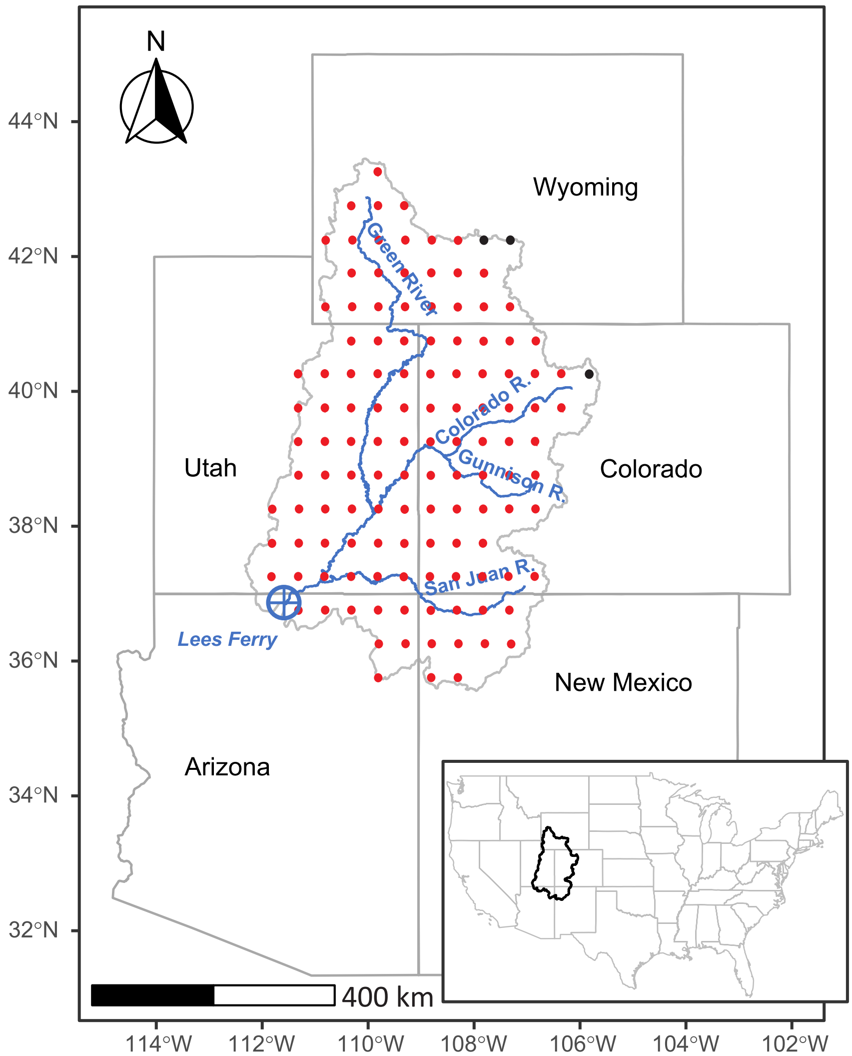

Figure 1. Upper Colorado River Basin (UCRB) (gray outline) with selected major tributaries (blue lines) and the Lees Ferry gage. Living Blended Drought Atlas grid points are shown; 122 with Palmer Drought Severity Index data, 1–2017 CE (red filled circles), and three with missing data for 1–209 CE (black filled circles). The southwestern United States location of the UCRB is shown in the inset.

2. Streamflow in the UCRB

2.1. Data

The two datasets used in this study to develop a Lees Ferry streamflow reconstruction include reconstructed Palmer Drought Severity Index (PDSI) from the LBDA archive (Cook et al., 2010; Gille et al., 2017) and naturalized streamflow data for the Lees Ferry gage (Reclamation, 2021a).

The LBDA utilizes all available tree-ring data that reflect variability in drought conditions using a nested reconstruction approach (Cook et al., 1999). Figure 1 shows the distribution of 125 LBDA grid-points in the UCRB used in this study. PDSI data are complete for the period 1–2017 CE for all except three gridpoints, and for those three gridpoints the data are complete for 210–2017 CE (Figure 1). Note that the 1979–2017 CE portion of the LBDA is instrumental rather than reconstructed PDSI.

Natural flow estimates for the Lees Ferry gage are available from Reclamation (2021a). The natural flow data used in this study include water years 1906–2021—this period (or any subset of years within this range of years) is considered for this study to be the instrumental, or observed data. The observed streamflow average for 1906–2021, 14.7 maf or 18.1 bcm, is used as the baseline for this study's analyses.

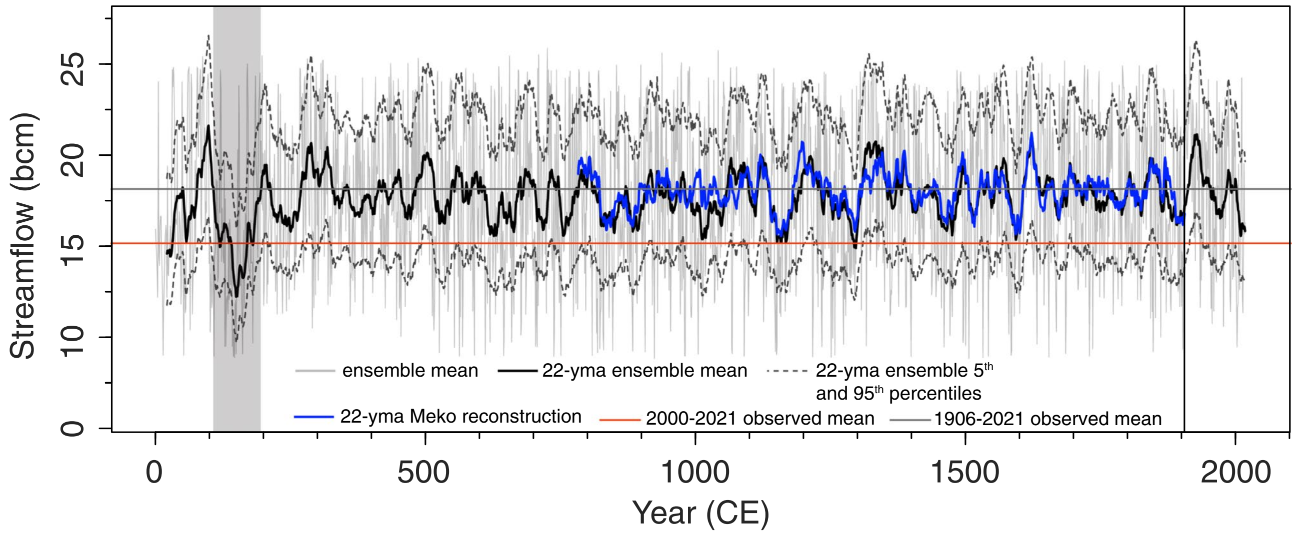

Figure 2. Ensemble mean reconstruction (thick gray line) with 22-year moving average (22-yma—right-aligned running mean) (thick black line). Ensemble mean 22-yma 5th and 95th percentiles are shown with black-dashed lines. The 22-yma Meko et al. (2007) reconstruction, truncated at 1905, is shown with a thick blue line. Two observed period means, 1906–2021 and 2000–2021 are thin horizontal lines in gray and orange respectively. Vertical black line indicates end of reconstruction, 1905, and start of verification period reconstructed values, 1906–2017. The gray shaded bar highlights the second-century drought interval.

2.2. Reconstruction and Verification

The reconstruction method, based on Gangopadhyay et al. (2009) (hereafter, G09), is a nonparametric approach. Details of the original method are described in G09 in the context of Colorado River reconstruction, and the method has recently been applied to streamflow reconstruction in central Asia (e.g., Zhao et al., 2022). In this new reconstruction, for any year prior to 1906, principal components analysis is used to identify the most similar years, *K*-nearest neighbors (*K*NNs), or *K* nearest neighbors, in the instrumental period, 1906–1999, and the *K*NNs are resampled to develop an ensemble of reconstructed flows. Similarity is judged statistically by projection of the PDSI vector for a reconstruction year on principal components of gridded reconstructed PDSI for the instrumental period. Repeated for each year, the procedure results in a 1,000-member ensemble reconstruction of annual flows for water years 1–1905 CE. The mean of the 1,000-member reconstructed streamflow ensemble represents the streamflow reconstruction (Figure 2). A 90% confidence interval for the reconstruction is provided by the 5th and 95th percentiles of the ensemble members.

Performance of the G09 method was evaluated using leave-one-out cross-validation (LOOCV) for water years 1906–2017 (total, 112 years; 2017 is the last year of the LBDA PDSI archive). The leave-one-out cross-validation (LOOCV) was conducted by cycling through each of the 112 years in sequence. For instance, for water year 1906, the remaining 111 years (water years, 1907–2017) were used to identify a maximum $K = 11$ years with a PDSI pattern most similar to that in 1906, and resampling was repeated to develop a 1,000-member reconstruction ensemble for 1906. The ensemble mean reconstruction, with upper and lower confidence limits, is compared to the instrumental streamflow record over water years 1906–2017 (Figure S1 in Supporting Information S1). The comparison indicates relatively good reconstruction skill. The mean streamflows are similar, while the standard deviation is lower for the ensemble mean reconstruction (see Figures S2a and S2b in Supporting Information S1). This lower standard deviation is expected: an individual ensemble member can generally have a standard deviation similar to that of the observed flows, but the ensemble mean reconstruction, which is an average representation of streamflows from the ensemble, results in compression of variance. The lag-1 autocorrelation for the ensemble mean reconstruction over this verification period is close to that of the instrumental streamflow (Figure S2c in Supporting Information S1). Drought statistics indicate that maximum duration and magnitude (deficit volume) in the observed data are closely matched in the reconstruction, while the maximum drought intensity (deficit volume per year) is slightly lower in the reconstruction (Text S1, Figure S3, and Table S1 in Supporting Information S1).

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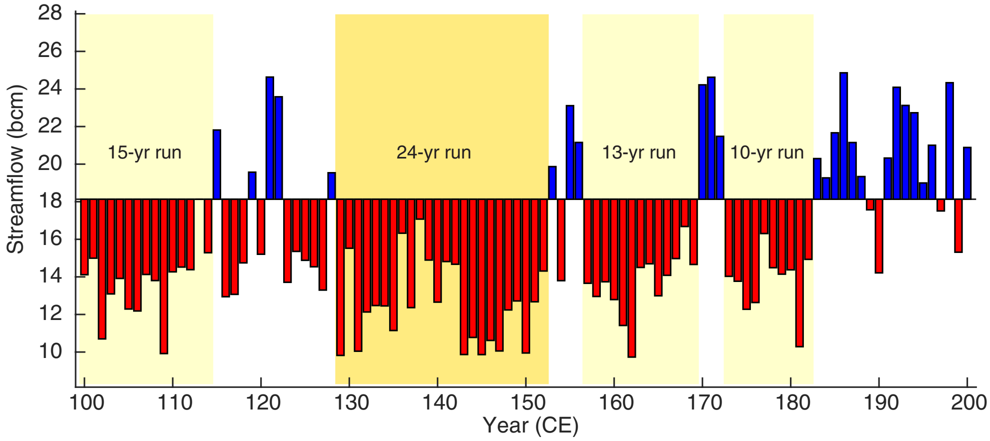

Figure 3. The second century portion of ensemble-mean reconstruction, emphasizing multiple runs of 10 or more years below the 1906–2021 observed Lees Ferry streamflow mean. Mean line at 18.1 billion cubic meter (bcm) (14.7 million acre-feet (maf)).

Skill of the new reconstruction, as measured by the Pearson correlation coefficient (r) of the ensemble mean reconstruction with instrumental streamflow, is comparable ($r = 0.78$; Figure S4 in Supporting Information S1) to that of the early portion of the Meko et al. (2007) reconstruction plotted in Figure 2. For example, the nested regression model supplying the 762–1181 CE portion of the Meko et al. (2007) reconstruction has a coefficient of determination, $R^2 = 0.60$, corresponding to $r = 0.77$ between reconstructed and instrumental streamflow. However, this skill is somewhat lower than that of Lees Ferry reconstruction models targeting more recent centuries and drawing on denser networks of tree-ring chronologies (e.g., Gangopadhyay et al., 2009; Meko et al., 2007; Michaelson et al., 1990; Stockton & Jacoby, 1976; Woodhouse et al., 2006).

3. The Current Drought in a 2,000 Year Context

The current period of drought has been found to be anomalous in the context of the instrumental record (Williams et al., 2022) and, as noted above, in the context of 1,200 years of reconstructed Colorado River streamflow reported in Meko et al. (2007). The new reconstruction now allows us to evaluate this drought over an even longer period of time. The Colorado River streamflow ensemble mean reconstruction, smoothed with a 22-year moving average, indicates periods of low flow in the mid-twelfth, late thirteenth, and late sixteenth centuries that appear roughly comparable to the 2000–2021 drought ongoing in the Colorado River. The most notable period of drought in the entire 1–1905 CE reconstruction occurs in the second century, with the 22-year average ending in 150 CE at 12.3 bcm (10.0 maf) or 68% of the instrumental mean (Figure 2). For comparison, the average annual flow of the 22-year drought, 2000–2021, is 84% of the instrumental mean (Table S2 in Supporting Information S1). When the 90% confidence interval is considered, the average annual flow for the second-century drought falls between 9.6 bcm and 16.8 bcm (7.8 maf and 13.6 maf), slightly overlapping the value for the observed 2000–2021 streamflow average (15.2 bcm or 12.3 maf). The second century also includes the lowest flows for periods averaged over three, five, and 10 years in the reconstruction and in the observed record (Table S2 and Text S2 in Supporting Information S1).

4. Features of the Second-Century Drought

The new Colorado River reconstruction shows four runs of persistently below average streamflow within the second century (Figure 3). The 24-year period, 129–152 CE, is by far the longest period of drought on record, and two others are the third and fifth longest, at 15 and 13 years (100–114 CE and 157–169 CE, respectively). The fourth is a 10-year drought, 173–182 CE, one of six 10-year droughts in this record, all of which occurred in the first millennium. Spatial patterns of these four droughts, based on the available gridded PDSI, show some

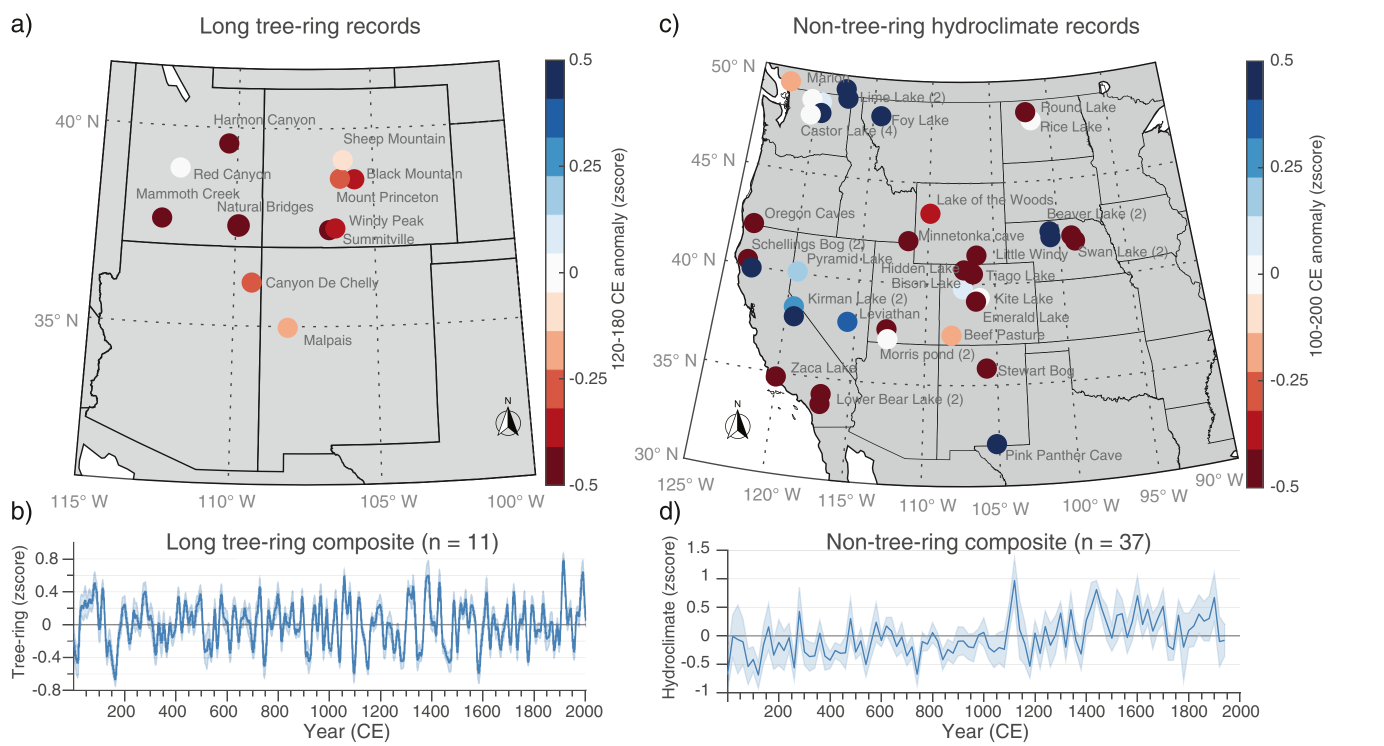

Figure 4. (a) Locations of 11 tree-ring chronologies that cover the second century, with tree-growth anomalies for 120–180 CE plotted by color. (b) Composite record of 11 tree-ring chronologies, 1–2000 CE. (c) Locations of 37 non-tree-ring paleohydroclimatic records, with anomalies for 120–180 CE plotted by color. (d) Composite record of 37 non-tree-ring records, 1–2000 CE.

variability, with the 129–152 CE period being the most intense but somewhat less extensive than the others (Figure S5 in Supporting Information S1).

In the 1,000 individual ensemble reconstruction members, the longest second-century drought (i.e., 129–152 CE in the ensemble-mean) ranges in duration from 12 to 46 years, with a duration of at least 24 years for 37% of the ensemble members. In contrast, the longest run (unbroken by an above average flow year) of Colorado River drought in the instrumental record is five years (1933–1937, 1988–1992, 2000–2004, and 2012–2016). Persistent droughts tend to reflect large cumulative deficits, and the four second-century droughts are no exception (in duration order, first, second, fifth and eleventh). However the annual average streamflow, a measure of drought intensity, in these long droughts is not as low as in some of the shorter droughts. For example, the most intense drought was the single-year drought, 1258 CE, at 8.1 bcm (6.6 maf) below mean flow compared to the annual average intensity over the 24-year period of drought, 5.7 bcm (4.6 maf) below the mean flow. When the three drought metrics—duration, magnitude, and intensity are taken together (Biondi et al., 2002), these four second-century droughts rank in the top 13, with the 129–152 CE drought ranking as most severe, overall (Table S3 in Supporting Information S1).

5. Additional Evidence for Drought in the Second Century

The second-century period of drought, as documented in this Colorado River reconstruction, appears exceptional in the context of the past two millennia. How well supported is this period, and what uncertainties underlie it? The second century occurs in the earliest part of the timespan covered by tree-ring data in the UCRB region. A total of 11 tree-ring chronologies in or near the UCRB extend into the second century (Table S4 in Supporting Information S1; Figure 4a). Data from most of these sites were incorporated into the tree-ring network used to reconstruct PDSI (Cook et al., 2010). Timeseries plots of these chronologies show a period of severe drought occurring at most of these sites over the middle to the end of the second century (Figure S6 in Supporting Information S1). The second-century drought is particularly notable in the Summitville (Routson et al., 2011),

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Harmon Canyon (Knight et al., 2010) and Mammoth Creek sites. Chronology values averaged for the 120–180 CE interval (Figure 4a) indicate that all of the sites reflect some level of drought except Red Canyon (Finley et al., 2020). This pattern is generally reflected in the gridded PDSI values averaged over the years 120–180 CE (Cook et al., 2010) (Figure S7 in Supporting Information S1). Regionally, the severity of the second-century drought, as documented by these chronologies, stands out in the context of the past 2,000 years. The median of the 11-chronology composite clearly shows the second century to be the worst drought in this region (Figure 4b). It is important to note that the number of samples in these long chronologies is much reduced going back in time and obtained primarily from remnant wood. Of the 11 tree-ring chronologies, approximately 63 individual tree samples include at least 4 years in the second century (Figure S8 in Supporting Information S1), and only two of these samples were from living trees—but, from Red Canyon, which does not reflect the second-century drought. During 100–200 CE, the number of trees for a given year ranges from 40 to 59.

There is clear evidence in the tree-ring data, sparse as it is, for second-century drought. However, it is difficult to precisely assess the severity and duration of drought conditions relative to other severe, sustained droughts because very few of the samples that reflect the second-century droughts extend through other droughts. There are only two series (from Summitville) that extend from the second century through the 1100s, which contains the most severe, sustained drought in the Colorado River in the past 12 centuries (Meko et al., 2007). While both suggest the second-century drought was more severe than the mid-twelfth century drought, this is not a robust assessment.

Other paleoclimatic data provide additional support for second-century drought (e.g., Routson et al., 2021; Shuman et al., 2018). A collection of 37 non-tree-ring hydroclimate records (e.g., pollen, diatoms, etc.) was assessed for evidence of the second-century drought (Table S5 in Supporting Information S1). Resolution and age control limit these records' ability to faithfully record events that occurred within multidecadal timescales. However, non-tree-ring hydroclimate records are useful because they are not limited by detrending and short segment lengths inherent in tree-ring chronologies (Cook et al., 1995). This collection of lower resolution records shows dry conditions occurred during the second century over a spatial domain broadly consistent with the tree-ring based evidence (Figure 4c). Furthermore, these records show a gradual pattern toward wetter conditions over the last two millennia (Figure 4d), with the driest conditions occurring in the early portion of the first millennium, coincident with the second century. This period also coincides with the higher frequency of longer and more severe droughts over the first millennium in the tree-ring records (Table S3 in Supporting Information S1). Further discussion on the second-century drought is provided in Supporting Information S1 (Text S3).

6. Conclusions

The new Colorado River streamflow reconstruction provides a record of streamflow variability and drought extending to 1 CE. The reconstruction reveals a second-century UCRB drought unmatched in severity by the current drought, 2000–2021 CE, or by any other reconstructed drought in the tree-ring record. Defining features of the drought are a single run of 24 consecutive years below the 1906–2021 observed Lees Ferry streamflow mean and three other runs of 10 or more years below the mean. Within the exceptional 24-year run, the lowest 22-year-mean flow is just 68% of the instrumental mean, compared to the 2000–2021 mean flow of 84%. Although uncertainty remains due to the sparseness of underlying tree-ring data in the reconstruction during the second century, exceptional drought is also supported by independent, non-tree-ring, paleoclimate proxy records. This new finding suggests that the range of natural hydroclimatic variability in the Colorado River is broader than previously recognized, setting a new bar for a worst-case scenario from natural variability alone. In order to confirm these findings, collection and analysis of more remnant wood from critical runoff producing watersheds of the UCRB could strengthen the reconstruction of the paleoclimatic record; especially useful for addressing relative severity of droughts would be long tree-ring records from trees that lived through both the second-century and medieval droughts.

Data Availability Statement

The ensemble reconstruction and supporting data can be accessed from the NOAA Paleoclimatology website, https://www.ncei.noaa.gov/access/paleo-search/study/36093.

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