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Key Points:

- Increasing drought duration on the Carson River has characterized the transition from the first to the second millennium
- Tree-ring chronologies show that the 2012–2015 drought on the Carson River is a less than one-in-a-century event
- Recent warming has exacerbated the hydrologic impact of 21st century precipitation droughts on the Carson River

Supporting Information:

- Supporting Information S1

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Long-Term Hydroclimatic Patterns in the Truckee-Carson Basin of the Eastern Sierra Nevada, USA

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Abstract The Truckee/Carson Basin, like other semiarid basins in the western United States, faces challenges to water management and planning under a changing climate. We analyzed tree-ring data, along with instrumental climatic and hydrologic records, to provide a perspective on extreme drought in the 21st century. Drought indices highlighted a recent increase in the average duration of hydroclimatic episodes: in the new millennium average duration was 74% longer for the 24-month Standardized Precipitation Index (SPI-24) and 62% longer for the Palmer Drought Severity Index (PDSI) than in the previous century. Average snow water equivalent (SWE) declined 7% per decade from 1965 to 2018. The 2012–2015 drought, in particular, stood out for its intensity and expression in snowpack, streamflow, and drought indices. Likely because of recent warming, this 4-year drought event had a very low likelihood based on observed Carson River flows from the first half of the 20th century. A 501-year tree-ring reconstruction (1500–2000 CE) of average water-year streamflow for the Carson River indicated that positive (wet) spells had slightly longer duration (mean of 2.7 years and range from 1 to 10 years) than negative (dry) intervals (mean of 2.4 years and range from 1 to 9 years). The early 1900s pluvial, that is, 1905–1911 in this record, was the third strongest episode in the entire reconstruction. The driest years were 1580 and 1934, both well-known widespread and severe droughts in the western United States. Noise-added reconstructions suggest that 2012–2015, while not unique in the 401 years prior to the start of the Carson River gaged flows in 1901, was a less than one-in-a-century event.

1. Introduction

Water supply shortages are capable of producing some of the worst environmental disasters, ranging from widespread crop failures to land degradation, with consequences that include human migration and permanent transformations in socio-ecological systems (Cook et al., 2014; Cook et al., 2015). In the western United States, drought impacts on forests and rangelands include reduced plant growth and carbon accumulation, increased wildfire suppression costs, and degraded rangeland conditions (Vose et al., 2016). Until 2016, parts of the Sierra Nevada were enduring a fifth consecutive year of drought, while California and Nevada had to cope with ever-increasing water demands for agricultural, urban, and environmental systems (Howitt et al., 2014; Williams et al., 2015). While the exceptionally wet 2016–2017 winter brought relief to this region (Wang et al., 2017), the southwestern United States is expected to experience drier winters in coming years (Cayan et al., 2010). In order to fully comprehend the severity of extreme droughts, and design policies that reduce vulnerability of water resources to projected impacts of global warming (Stakhiv, 2011), a long-term perspective is required (Cook et al., 2010; McCabe-Glynn et al., 2013; Wahl et al., 2017).

Instrumental records over the past century have shown that the seasonal discharge regime of rivers and streams in the western United States varies substantially from year to year in response to the varied impact of large-scale ocean and atmospheric climate oscillations (Cayan et al., 1999; McCabe et al., 2004; McCabe et al., 2008; McCabe & Wolock, 2009). At the same time, climate model simulations based on greenhouse warming show that moisture stress in the western United States is likely to increase (Garfin et al., 2013; Seager et al., 2007), with possibly drastic transformations of ecosystems and landscapes in the next decades as a consequence of severe heat waves and their effects on forests (Allen et al., 2010; Millar & Stephenson, 2015; Trumbore et al., 2015; Williams et al., 2013). Properly evaluating modern changes and the likelihood of future changes benefits from a historical perspective that goes beyond the instrumental record to capture underlying long-term dynamics that would

Figure 1. Map of Truckee (lime fill color) and Carson (purple fill color) River Basins (red boundaries). Locations of tree-ring chronologies (green circles; Contributors of the International Tree-Ring Data Bank, 2014), state boundaries (dark black lines), and Climate Divisions (light blue lines; Guttman & Quayle, 1996) are also shown. The Truckee-Carson watersheds are included in the area covered by Nevada Climate Division 1 (NV1) and California Climate Division 3 (CA3).

otherwise be impossible to detect (National Research Council, 2006). The short instrumental record cannot fully capture the extent of hydroclimatic episodes lasting several decades that have affected the Sierra Nevada (e.g., Kleppe et al., 2011) and sometimes impacted widely separate major river basins of the western United States simultaneously (MacDonald et al., 2008; Meko et al., 2007).

Water resources issues currently confronting managers and planners in the western United States are embodied in the Truckee/Carson Basin (Figure 1), which drains the eastern slopes of the Sierra Nevada, in California, and maintains terminal lakes of the western Great Basin, in Nevada. “Packed into this relatively small Basin is every form of water use and every type of water user that exists in the Western United States, including: tribal lands and trusts; irrigated agriculture; municipalities and industry; mining and geothermal energy exploration; Federal water projects; hydropower generation; lake, stream, and reservoir recreation; and restoration efforts for diminished wetlands and endangered aquatic species. Correspondingly, the diversity of water uses within its borders has made the Basin home to every type of water resources conflict.” (Bureau of Reclamation, 2015). Mean annual runoff from these basins, which mostly originates as snowmelt in the Sierra Nevada, is about $27.2 \text{ m}^3/\text{s}$ (Moosburner, 1986), with extremely high variability (Crippen, 1986), both spatially (from the upper to the lower elevations) as well as temporally (from annual to interdecadal). The Truckee and Carson Rivers are important for fish and wildlife, hydroelectric power, and water supply in Nevada and California. The Truckee River (Berris et al., 2001) is associated with Lake Tahoe, a center of tourist attraction and recreation that drives local economic activities. The Carson River (Hess, 1999), which is characterized by relatively natural flows compared to the Truckee River, is the key source of water for agriculture in the Fallon area. The Truckee and Carson Rivers are linked hydrologically by the transfer of flow at Derby Dam from the Truckee to the Lahontan Reservoir on the Carson (Moosburner, 1986). Residual flow of the

Truckee ends up in the closed basin of Pyramid Lake, while the residual flow of the Carson terminates in the Carson Sink.

In order to best evaluate the modern variability of hydroclimatic episodes in the Tahoe/Truckee/Carson Basins it was necessary to provide a context longer than the instrumental record, because record extension can improve estimates of average, extremes, and overall probability distributions of hydroclimatic parameters (Salas et al., 2008). Proxy records derived from growth layers of long-lived tree species have been used to augment time series not only of streamflow (Meko et al., 2001) but also of precipitation (Gray et al., 2004), soil moisture (Yin et al., 2008), snow water equivalent (SWE; Woodhouse, 2003), Palmer Drought Severity Index (PDSI; Cook et al., 2004), standardized precipitation index (Touchan et al., 2005), flood events (St. George & Nielsen, 2003), and lake levels (Bégin, 2001). Proxy reconstructions of hydrological variables, including streamflow, are generally produced by statistical regression of a single parameter, such as water-year total river discharge, on tree-ring chronologies, or some linear combination of chronologies. The more advanced statistical models allow for special treatment of persistence and quantification of the uncertainty of reconstruction (Cook et al., 2013; Meko & Woodhouse, 2011; Salas et al., 2014).

In this study, we evaluated long-term hydroclimatic variability in the Truckee-Carson basin using both instrumental and proxy records. In particular, our objectives were (a) to place the most recent droughts and wet spells in a longer historical context, (b) to determine if recent episodes were anomalous with respect to the range of natural variability, and (c) to obtain an updated assessment of water resources in western U.S. watersheds toward improving science-based management and risk assessments. Numerical and graphical tools were applied to examine the likelihood of extended episodes, which represents one of the main issues facing water resource planners.

2. Materials and Methods

2.1. Instrumental Records

Climatic Division data for water years 1895–2017 were analyzed for the two divisions that include the Tahoe/Truckee and Carson River watersheds (Figure 1), that is, Nevada Division 1 (Northwest) and California Division 3 (Northeast Interior Basins). Water-year summaries of mean temperature and total precipitation were computed in order to remove the annual cycle and uncover time series trends. The monthly values of two drought indices (Heim, 2002), PDSI, and SPI-24 (Standardized Precipitation Index for a 24-month window) were analyzed in terms of dry and wet episodes, with a focus on potential changes in the new millennium compared to the previous century.

The 1 April SWE data were used to summarize changes in water availability from the mountain snowpack, which is a critical source of runoff for the study basins. SWE records from 11 snow course stations in the Lake Tahoe and Truckee River watersheds were downloaded from the California Data Exchange Center (California Data Exchange Center, 2018) and were checked for consistency with records available from the Natural Resources Conservation Service (Natural Resources Conservation Service, 2018). SWE for individual stations starts as early as 1910, and for all except one station extends through the winter of 2017–2018 (Table S1 and Figure S1 in the supporting information). Each station time series was converted to percentage of normal, which is defined as the long-term mean for years with no missing data, and the average of the percentage series was used to describe the regional 1910–2018 SWE variability. A regression line against year was overlaid on the summary SWE series, and significance of time series trends was tested nonparametrically using the Mann-Kendall statistic (Hipel & McLeod, 1994), augmented with block bootstrap to account for temporal autocorrelation (McLeod, 2015).

To quantify Truckee and Carson River streamflow, monthly total discharge was obtained from the U.S. Geological Survey (U.S. Geological Survey, 2018) for six stations on the Truckee River and three stations on the Carson River (Table S2). Monthly flows were aggregated by water year (October–September) for each station, and a single time series representing each basin was computed by averaging normalized, or z-score (zero mean, unit standard deviation) water-year flows. Common-period station means and standard deviations of annual flows (Table S2) were used for z-score conversion. The common period water-year flows for both rivers is 1901–2017, during which the Truckee had no missing values in its six-station average (Figure S2), and Carson had missing values in 1908 and 1911 (Figure S3). Those two missing values for the Carson were filled in using the Truckee z-scores. The 2018 water-year data were not fully available at the time of this analysis.

The Carson River z-score series of annual flows is the predictand in our reconstruction model (described below). Ideally, such a predictand should be minimally affected by nonclimatic influences, including reservoir storage and irrigation diversions. We chose our three streamflow gages to be upstream of any major reservoir, with two of them located in the upper reaches of the watershed. While some distortion of the flows cannot be fully ruled out because irrigation has a long history in the basin (Hess & Taylor, 1999), the synchronicity of z-score time series (Figure S2) suggests that irrigation changes over time have had little influence on the variability of the composite z-score Carson flow series.

2.2. Tree-Ring Reconstruction and Episode Analysis

Water-year streamflow was reconstructed from chronologies of standardized tree-ring width using as predictor an average of western U.S. tree-ring chronologies available from the public-domain International Tree-Ring Data Bank data set (Contributors of the International Tree-Ring Data Bank, 2014), augmented with chronologies we developed for other projects in the Sierra Nevada and the Great Basin (Biondi, 2014; Meko et al., 2014). A weighted average of the predictors, where the weights were based on linear correlations between predictand and predictors, performed roughly the same as their mean, making the simpler method preferable. The initial screening was performed by computing linear correlations between the Carson or the Truckee River water-year streamflow and tree-ring chronologies that (a) ended on or after year 2000, (b) started on or before year 1500, (c) were based on a minimum of three samples per year, and (d) were located between 113–125°W and 30–50°N. To ensure temporal stability of relationships, tree-ring chronologies were retained only if they had correlation $r \geq 0.40$ with both the first half (1900–1958) and the second half (1959–2017) of the flow record. As fully mentioned in section 3, the Carson flow records were more consistent from

station to station, and the average time series was slightly better correlated with the tree-ring chronologies, most likely because of lower flow regulation in the Carson basin (Hess, 1999). The reconstruction was therefore performed for the Carson streamflow.

Record extension was attained by regressing the flow series, y_t , on the mean of all selected tree-ring chronologies, $x_{t,1}$. From examination of the scatterplot of y_t on $x_{t,1}$, a two-piece segmented regression (Weisberg, 2014) was selected and calibrated on the full overlap of flow and tree-ring index:

$$y_t = b_0 + b_1 x_{t,1} + b_2 (x_{t,1} - x_0) x_{t,2} + e_t \quad (1.1)$$

where b_0, b_1 , and b_2 are parameters estimated by least squares; x_0 is a specified value of tree-ring index such that one fitted straight-line segment applies to $x_{t,1} \leq x_0$ and the other segment to $x_{t,1} > x_0$; $x_{t,2}$ is a dummy variable equal to 0 if $x_{t,1} \leq x_0$ and to 1 if $x_{t,1} > x_0$; and e_t is the noise term. The model was fit using Matlab function REGSTATS and implemented for reconstructions using function LSQ_LUT_PIECEWISE from the MathWorks File Exchange (MathWorks, 2018). Estimated residuals, $\hat{e}_t$, were checked for violation of regression assumptions on normality, autocorrelation, and relationship to fitted values (Weisberg, 2014). The model was validated with leave-one-out cross-validation (Michaelsen, 1987), and the root-mean-square error (RMSE) of cross-validation residuals was used along with assumption of normality of residuals to establish reconstruction confidence limits. A single-line model, or simple linear regression ($b_2 = 0$) was also explored to test sensitivity of reconstructed values to model choice.

Instrumental and reconstructed time series were analyzed in terms of consecutive runs or episodes above (or below) an arbitrary reference level (Biondi et al., 2008; Salas, 1992; Salas et al., 1980). An episode can be characterized by its length (or duration), magnitude (or run-sum), intensity, and peak. Length (L) is the number of time steps continuously above or below the threshold. Magnitude (M) is the sum of departures for a given episode duration. Intensity ($I = M/L$) is the average annual departure or mean annual magnitude. Peak is the maximum absolute departure for a given episode. Analysis of episode parameters allows an objective identification of the “strongest,” “greatest,” or “most remarkable” periods, and although this approach is normally used for drought analysis, it can be applied to any cumulated deviations (Biondi et al., 2008). Given that the most important features of a drought, especially for long-term planning purposes, are its duration and magnitude (Biondi et al., 2005), only these two parameters were used in the comparison of episodes (e.g., droughts). When using normalized values, the threshold was set at a z -score of zero. Each episode parameter was ranked separately, and the two ranks were added to obtain the final episode score; the higher the score, the stronger the episode. Other ranking schemes and/or ways to score time series episodes could have provided somewhat different results, but the approach followed here, albeit relatively simple, is well supported by advanced statistical theory (Kozubowski & Panorska, 2005, 2008).

Drought-related statistics L , M , and I were also applied in two types of probability analysis to place the recent (2012–2015) Carson River drought in historical context using observed and reconstructed Carson River flows. For these analyses the drought threshold was set at the lowest tercile of all instrumental water-year values, that is, percentile 100/3 of the observed 1901–2017 z -score Carson flows. The intensity of the 2012–2015 4-year drought was defined as the “critical intensity,” I_c . In the first analysis, exact simulation (Percival & Constantine, 2006) was applied to estimate the probability of a critical-intensity drought of length $L \geq 4$ years in 58 years (second half of the gaged record) from variability of flows as represented by the first half of the gaged record. Carson flows were converted to a normal distribution before this simulation analysis using an ogive curve (Panofsky & Brier, 1968) to satisfy assumptions of exact simulation. In the second analysis, the recent drought was placed in long-term context with noise-added flow reconstructions (Meko et al., 2001). In this approach, tree-ring reconstructed flows are added to noise sampled from a normal distribution with standard deviation equal to the RMSE of the cross-validation residuals of the reconstruction model. Each noise-added reconstruction is a plausible realization of the unknown actual flows given the reconstruction and its uncertainty. The ensemble of noise added reconstructions was used to estimate the likelihood that $N \leq n$, $n = 0, 1, 2, \dots$ droughts of critical intensity and length $L \geq 4$ years were experienced in the four centuries prior to the start of gaged flows.

Figure 2. Time series of monthly drought indices for the two climate divisions (CA3 and NV1) that include the Truckee and Carson watersheds. Records begin in January 1895 and were plotted up to December 2017. PDSI (top) = Palmer Drought Severity Index; SPI-24 (bottom) = Standardized Precipitation Index over a 24-month window. Data downloaded from <ftp://ftp.ncdc.noaa.gov/pub/data/cirs/climdiv/>.

3. Results

3.1. Instrumental Records

Precipitation and temperature time series from California Division 3 and Nevada Division 1 covary at inter-annual and interdecadal time scales, with the former cooler and wetter than the latter, as expected (Figure S4). The warmest years were 1934 and 2015, with 1934 slightly higher in Nevada (11.69 versus 11.64 °C), and 2015 slightly higher in California (9.50 versus 9.45 °C). The wettest California water year, 2017, ranked fourth wettest in Nevada. The wettest Nevada water year, 1998, ranked 15th wettest in California. Drought indices standardized to remove differences in average climatic regime (Keyantash & Dracup, 2002) are also in excellent time series agreement, with both PDSI and SPI-24 time series showing a tendency for longer drought durations in the second millennium (Figure 2).

The overall slower-varying behavior of SPI-24 compared to PDSI is reflected in the number of episodes: 89 for SPI-24, with average duration of about 16 months considering both positive and negative ones, and almost twice as many episodes (170) for PDSI, with average duration of about 9 months. This pattern remained in the new millennium, with about half as many dry and wet spells recorded by SPI-24 (8 episodes, with average duration of 26 months) than by PDSI (17 episodes, with average duration of 13 months). However, in the new millennium episodes were of considerably longer average duration (74% longer for SPI-24 and 62% longer for PDSI) than in the previous century.

The two longest droughts according to PDSI (Table S3) were in the past two decades, from March 1999 to September 2004, for a total of 67 very dry months (resulting in the highest episode magnitude), followed by the September 2011 to April 2015 episode, spanning 44 months. This 44-month drought was equaled in

Figure 3. 1 April SWE, 1910–2018, in Truckee and Lake Tahoe watersheds. The plotted time series is percentage of common-period mean snow water equivalent averaged each year over snow course stations with data. The number of available stations is annotated at decadal intervals along the *x* axis. Fitted trend line (dashed) is a least squares fit for the second half of the record (1965–2018). While the line has a negative slope, there is no statistically significant time series trend according to the Mann-Kendall test either in this period (p -value = 0.104) or for the whole record (p -value = 0.494).

length during the “Dust Bowl” episode, which in this record extended from October 1930 to May 1934, but with lower magnitude than the 2000s droughts. The late 1950s drought received the same overall score as the 1930s drought, having a slightly shorter duration (40 months, from October 1958 to January 1962) but a slightly higher magnitude. The top five episodes in the PDSI ranking were all dry spells, with the fifth one also being in the 2000s, from May 2006 to February 2009. Using SPI-24, the longest drought was the Dust Bowl episode from October 1928 to December 1935, for a total of 87 months. However, the strongest episode in the SPI-24 record is not a drought, but the early 1900s pluvial, from February 1904 to December 1911, a total of 95 wet months. Indeed, the SPI-24 ranking placed three wet spells in the top five, as the second-strongest drought, from December 1987 to April 1994 (77 months), was ranked below two other wet spells, February 1979 to July 1985 (78 months) and March 1995 to April 2000 (62 months).

Snowmelt dominates streamflow in the Sierra Nevada, as evidenced for the Carson River by a 4- to 5-month lag in monthly hydrograph peaks of precipitation and discharge (Figure S6). The two longest snowpack droughts as measured by consecutive years with SWE < 100% occurred in the most recent third of the record: a 6-year drought in 1987–1992 and a 5-year drought in 2012–2016 (Figure 3). The most recent drought stands out for three consecutive years (2013–15) with less than half of normal 1 April SWE. Of the 14 total years with SWE < 50% since 1910, this is the only consecutive-year event. A downward trend in percentage-of-normal SWE over the second half of the record (1965–2018) was stronger (7% per decade) than over the full record (Figure 3). The slope of the fitted trend line did not reach statistical significance, and there was no significant trend also according to the Mann-Kendall test (p -value = 0.104). Since about 1950 the envelope encompassing very high and very low SWE events showed a downward trend, suggesting less extreme highs and more extreme lows. The highest and lowest SWE were in 1952 and 2015, respectively.

The three Carson gauges had essentially the same pattern of annual streamflow variation over the available record (Figure S2), whereas the Truckee gauges presented some differences between stations (Figure S3). When plotted on the same graph, the water-year streamflow series are overall quite similar, and with less pronounced low flows in the Truckee (Figure 4), most likely because the flows are regulated rather than natural. Carson annual flows, 1901–2017, are barely significantly autocorrelated at lag 1 ($r_1 = 0.21$) and less so than Truckee flows ($r_1 = 0.38$), also probably due to regulation of the Truckee (Figure S8). Because the variability of stream discharge in these two basins is remarkably similar at interannual to interdecadal time scales, the Carson River streamflow is a most useful analog for examining long-term hydroclimatic variability in the region.

The close connection between stream discharge in both basins and regional climatic patterns that control water-year precipitation is further revealed by correlation maps between average streamflow and water-

Figure 4. Average river discharge (in standard deviation units, sdu) for the water year (October through September) in the Carson and Truckee Basins. Series for the Carson, 1901–2017, computed from three gauging stations (Figure S2), and for the Truckee, 1900–2017, from six stations (Figure S3). Streamflows covary at interannual and interdecadal time scales and show high values during the two strong El Niño episodes of 1982–1983 and 1997–1998, as well as during the early 1900s pluvial and the exceptional 2017 water year.

year total precipitation from all Climate Divisions in the conterminous United States (Figure 5). Moving into areas where El Niño–Southern Oscillation effects on climate regime are typically stronger, that is, the American Southwest and Pacific Northwest (Brown & Comrie, 2004), correlations decline rapidly toward zero, although very strong El Niño years, such as the 1982–1983 and 1997–1998 events (An & Jin, 2004), corresponded to very high streamflow on the Truckee and Carson Rivers (Figure 4).

3.2. Tree-Ring Reconstruction and Episode Analysis

Correlations between streamflow and all tree-ring chronologies initially available (a total of 1,029) were on average slightly higher for the Carson than for the Truckee, even though the spatial patterns over the western United States were quite similar (Figure S7). The initial selection criteria, which guaranteed a record extension of at least 400 years, corresponding to a fivefold increase of the instrumental length, identified many more predictors for the Carson River streamflow during the most recent period (1959–2017; 59 predictors) than for the earlier period (1901–1958; 24 predictors). To favor temporal stability, the tree-ring network

Figure 5. Map of linear correlations between total water-year precipitation in U.S. Climate Divisions and total water-year streamflow for the (left) Carson and (right) Truckee rivers, 1901–2017 (see Figure 4). Point values, plotted at the center of the climate divisions, are shown by blue upright triangles when positive, and by red inverted triangles when negative, with symbol size proportional to the correlation value. Interpolated surfaces are plotted using blue shades for positive values, and the red shades for negative ones. Geographical pattern of positive correlations indicates that river discharge, and associated freshwater resources, is controlled by large-scale climatic patterns that also determine the variability of precipitation in the western United States, especially in the Sierra Nevada and nearby regions.

Figure 6. Location of 22 tree-ring chronologies used to reconstruct water-year streamflow for the Carson River. Symbols identify the tree species (solid for conifers, empty for hardwoods), which are mostly pines (nine chronologies total, six from foxtail pine and one each from limber, ponderosa, and single-needle pinyon pine), followed by blue oak (six chronologies) and western juniper (five chronologies), with an additional big-cone Douglas-fir and a giant sequoia chronology. Additional information on these 22 chronologies is provided in Table S4.

of predictors for the reconstruction model was restricted to the 22 tree-ring chronologies in common to the two sets of predictors (Figure 6 and Table S4).

Among these 22 predictors there was a predominance of *Pinus* species (six *balfouriana*, one *ponderosa*, one *monophylla*, and one *flexilis*), followed by blue oak (six *Quercus douglasii*), western juniper (five *Juniperus occidentalis*), big-cone Douglas-fir (one *Pseudotsuga macrocarpa*), and giant sequoia (one *Sequoia giganteum*). Record extension was preferable when using a piecewise (or segmented) linear regression with the mean of all 22 predictors, which explained 61% of the streamflow variance during the period of overlap with the instrumental data (1901–2000; Figure 7). Model statistics and estimated parameters are listed in Table 1. The large difference in RMSE between the two pieces of the segmented line model reflected the small scatter around the fitted line through the lowest tree-ring indices (Figure 7). Accordingly, uncertainty of

Figure 7. The relationship between Carson streamflow and the arithmetic mean of the 22 tree-ring chronologies was modeled using least-squares regression. The single-line fit (red line) performed poorly for very low flows during the calibration period. A piecewise (or segmented) two-line fit (black line) was then selected for the final reconstruction.

dry years, 2012–2015 (Figure 8b). For the lowest-tercile threshold (-0.54 sdu), 2012–2015 ties with 1928–1931 as the longest ($L=4$ years) drought but is more intense ($I_c = 0.55$ sdu). Accordingly, 2012–2015 was used to define the critical intensity for subsequent analyses. Exact simulation, using 10,000 simulations of 1960–2017 flows from the time series properties of the 1901–1959 flows, yields a marginally low probability ($p = 0.013$) that a critical-intensity drought of length $L \geq 4$ years could have arisen from natural variability as described by observed flows prior to 1960.

The noise-added tree-ring reconstructions give an additional perspective on the recent drought. Although there is a strong hint of reduced reconstruction uncertainty for very low tree-ring indices (Figure 7), we used the larger $RMSE_v$ for the full model (Table 1) in generating the noise. The perspective from noise-added reconstructions extends over the 401-year preinstrumental period 1500–1900 CE (Figure 8a). The number of critically intense droughts of length $L \geq 4$ years was counted for each of 10,000 simulations to derive the probabilities plotted in Figure 9. The probability is $p = 0.21$ that the period 1500–1900 contained no critical droughts (critical intensity and length $L \geq 4$ years). In other words, it is more than likely

($p = 0.79$) that the Carson River experienced at least one critical drought over the 1500–1900 CE interval. On the other hand, the tree-ring record gives an extremely high probability ($p > 0.99$, $N \leq 4$ years) that the recent drought is less frequent than a one-in-century event, that is, no more than four such events are likely to occur in 401 years.

Table 1
Statistics^a of Reconstruction Models^b Used to Extend the Carson River Streamflow Back to 1500 CE

Model	R^2	RE	RMSEc	RMSEv		
				Full	A	B
Two line	0.61	0.60	0.6056	0.6223	0.1001	0.6481
One line	0.60	0.59	0.6207	0.6297	-	-

^aCalibration R^2 and validation reduction of error (RE) are dimensionless, while root-mean-error of calibration (RMSEc) and three measures of RMSE from leave-one-out cross-validation (RMSEv) are in standardized (z-score) flow units. “Full”: computed for the full set of 100 observations (1901–2000), “A”: computed for the leftmost regression line segment (i. e., for the lowest tree-ring indices), and “B”: for the rightmost segment. The two-line model and RMSEv for the full period were used, along with the assumption of normality, to generate noise added reconstructions.

^bTwo-line (segmented) regression equation: $y = -1.3682 + 0.5583 x_1 + 3.2285 (x_1 - 0.73) x_2$; one-line regression: $y = -1.3682 + 3.5065 x_1$.

reconstruction is likely much smaller for extremely low tree-ring indices than for higher tree-ring indices. Analysis of residuals showed approximate normality, yielded no significant autocorrelation (Durbin-Watson = 1.67, $p > 0.05$) and no strong pattern in a scatterplot of residuals against fitted values.

The reconstructed time series (Figure 8a) was analyzed in terms of episode duration and magnitude (Table 2). On average, the 98 positive (wet) and 98 negative (dry) spells had slightly longer duration for the former (mean of 2.7 years and range from 1 to 10 years) than for the latter (mean of 2.4 years and range from 1 to 9 years). The two strongest episodes (1978–1986 and 1740–1747) as well as the longest one (1888–1897) were wet periods. A third positive episode, the early 1900s pluvial (Cook et al., 2011; Woodhouse et al., 2005), that is, 1905–1911 in this record, equaled the strongest drought (1776–1783) in the entire reconstruction (Table 2). Even though not included in the three strongest episodes, the driest years in the reconstruction were 1580 (-1.25 sdu) and 1934 (-1.09 sdu), both well-known widespread and severe droughts in the western United States (Cook et al., 2010; Cook et al., 2014; Woodhouse et al., 2010).

3.3. Probability Analysis

The time series plot of 1901–2017 z-score flows indicated several multiyear departures from normal, the most recent of which is a sequence of four

4. Discussion

Runoff from about one third of the 200 largest rivers has changed significantly since the 1950s (Dai et al., 2009), but having much longer (century-scale) information on seasonal runoff variability for individual watersheds helps with constraining climate model projections (Yang et al., 2018). The Truckee-Carson river system is dependent on the amount or size of accumulated snowpack, which can be highly variable from year to year. Simply stated, the larger the snowpack, the greater the streamflow. Beginning in 2012, snowpack accumulations in the Truckee River Basin have been well below the long-term average (Tahoe Environmental Research Center, 2015; p.7.8). Although water year 2015 had the lowest

Figure 8. (a) Time series plot of normalized water-year streamflow (sdu = standard deviation units) reconstructed from a piecewise (or segmented) linear regression with the average of 22 tree-ring chronologies from the western United States. Instrumental records (red curve) used for calibration covered the 1901–2000 period and are the same as those shown in Figure 8b. Visual inspection shows that the 501-year reconstruction (1500–2000 CE) is more effective at capturing droughts than very wet periods, such as the early 1900s pluvial and the El Niño events of the early 1980s and late 1990s. Episodes (gray shading) above or below the zero reference level were analyzed in terms of their duration and magnitude (Table 2). (b) Normalized (z-score) average water-year streamflow for the Carson River from 1901 to 2017. Thresholds are marked at normal, or a z-score of zero (dashed black horizontal line), and at the lowest tercile (−0.54 sdu; solid red horizontal line). The tercile threshold marks 4 years as the longest episode (or run), and the most severe 4-year run was measured by its intensity in 2012–2015.

Table 2
The 10 Strongest Episodes Identified in the 501-Year (1500–2000) Reconstructed Streamflow

Start (year)	End (year)	Episode	Dur (years)	Abs Mag	Dur Score	Mag Score	Score
1978	1986	Pos	9	9.6	194	196	390
1740	1747	Pos	8	7.7	192	195	387
1776	1783	Neg	8	5.3	192	192	384
1905	1911	Pos	7	6.4	190	194	384
1562	1568	Pos	7	6.2	190	193	383
1515	1523	Neg	9	4.4	194	188	382
1888	1897	Pos	10	4.3	196	186	382
1995	2000	Pos	6	5.1	178	191	369
1601	1606	Pos	6	4.4	178	187	365
1590	1595	Neg	6	4.1	178	184	362

Note. See Figure 8a for a time series plot. Positive (Pos) episodes indicate wet periods; Negative (Neg) episodes indicate dry periods. The two episode parameters (duration and absolute magnitude) were separately ranked (with increasing ranks for increasing values), and the two ranks (DurScore and MagScore) were added to obtain the final Score (the higher its value, the stronger the episode).

snowpack in recorded history, water year 2017 was exceptionally wet, reaching hydrologic maxima at several recording stations.

Our analysis of 1 April SWE further shows that SWE in the study area reflects well-documented California droughts in the late 1980s to early 1990s, and in the early 21st century. The record high 1952 SWE in terms of percentage of normal appears to have been driven by high snowpack at lower elevations (Figure S1). Year 1952 also happens to stand out for a relatively large error in various tree-ring reconstructions of streamflow and snowpack (Belmecheri et al., 2016; Meko et al., 2001) and falls among the 10% of wettest years, in the Central Valley of California according to a 1557–2000 CE reconstruction of annual precipitation from blue oak samples (Meko et al., 2011). Warming has been recognized as a factor for SWE decline in the West (Mote et al., 2005; Mote et al., 2018), and dust deposition has also played an important role (Painter et al., 2010; Painter et al., 2018). The high interannual variability that characterizes SWE and other hydrological variables in this region hampers detection of trend in mean over short periods, such that a null hypothesis of no SWE trend could not be rejected at $\alpha = 0.01$. Still, a decline of 7% per decade is practically large, and regardless of its cause deserves careful consideration in resource planning.

Figure 9. Tree-ring context for the 2012–2015 Carson River drought from observed flows and noise-added reconstructions. Results were derived from 10,000 noise-added reconstructions. Probability of N or fewer critical droughts ($L \geq 4$ years and $I \geq I_c$) in the preinstrumental period covered by tree rings (1500–1900). Horizontal axis truncated at the largest n for which $L \geq 4$ years.

Until the most recent droughts, water planning for the Truckee Meadows Water Authority, which supplies the Reno metropolitan area, was based on the hydrology of 1987–1994 as an analog for a worst-case scenario. When both duration and magnitude are considered since January 1895 (Table S3), this drought event is indeed the second strongest one according to SPI-24, with the Dust Bowl drought taking the top position among dry spells. Using PDSI, on the other hand, this particular episode is not included among the top ten ranks, which are still occupied mostly by negative episodes. The top five PDSI episodes are all negative (i.e., droughts), with three of them in the new millennium. These three droughts are, in descending order, the early 2000s episode (March 1999 to September 2004), the most recent one (September 2011 to April 2015), and the one sandwiched between the 2005 and 2011 wet years (May 2006 to February 2009).

Using SPI-24, the five strongest episodes included more wet (three) than dry (two) spells, with the early 1900s pluvial occupying the top rank. In second position was the Dust Bowl drought, followed by two wet spells, both associated with strong El Niño episodes: these two wet spells range from February 1979 to July 1985 and from March 1995 to April 2000.

The difference in ranking between PDSI and SPI episodes was likely caused by air temperature, higher during the most recent dry spells than in the past (Figure S4), and pushing PDSI values lower without affecting SPI-24. Besides this clear evidence for hotter droughts in 2000–2017, these two instrumental metrics have shown longer average durations of hydroclimatic episodes than during their previous 100+-year record.

It should be mentioned that climate division data have been recently revised to improve their quality (Vose et al., 2014), and the new version was used in this article. The new Climate Division records incorporate data from the high-elevation Snowpack Telemetry (SNOTEL) network, which are particularly relevant for the topographically complex landscape of the western United States. On the other hand, SNOTEL data were found to be affected by warming artifacts and sensor biases that when propagated into climate data sets that incorporate them, including the well-known PRISM products (Daly et al., 2008), have most likely amplified the “1981–2012 western U.S. elevation-dependent warming by +217 to +562%” (Oyler et al., 2015). PRISM, the Parameter-elevation Regressions on Independent Slopes Model, is a topographically driven interpolation algorithm, and in its original version (Daly et al., 1994) climatic data used as input for the model did not undergo any time-discontinuity screening, either for urban heat island effects or for changes in station location or instrumentation. Because of this, PRISM output, albeit extremely useful in the spatial domain, may be unreliable for time series analysis or temporal trend detection. Both Climate Division and PRISM time series are routinely used for climate change assessments (e.g., Garfin et al., 2013), normally without mention of such caveats.

The main value of proxy records is that they provide much longer time series than the available instrumental climate record. Numerous other dry and wet episodes become available to evaluate if the second millennium, and particularly the current drought, have been unusual compared with episodes in earlier centuries. The extremely high interest, and demand, for a longer perspective on drought is highlighted by recent dendroclimatic studies. For example, Griffin and Anchukaitis (2014) placed the 2012–2014 California drought in a long-term context using a new reconstruction of cool-season precipitation, 1293–2014, from blue oak (*Quercus douglasii*) together with an existing reconstruction of PDSI, 800–2006, from the North American Drought Atlas (Cook et al., 2004; Cook et al., 2010). The PDSI reconstruction was scaled such that its variance matched that of the instrumental PDSI and was then padded with instrumental PDSI after 2006. The reconstruction data are available online from the National Oceanic and Atmospheric Administration Paleoclimate website, <http://www.ncdc.noaa.gov/paleo/study/17556>. The precipitation reconstruction identified 2012–2014 as one of several unusually dry events—but not the most severe episode—back to 1293, while the PDSI analysis marked 2012–2014 as the most severe 3-year drought of the past 1200 years.

A second example of tree-ring context for the recent California drought was a reconstruction of 1 April SWE in the Sierra Nevada for the 1500–1980 period, based on the precipitation signal of blue oak in combination

with a temperature signal from a separate tree-ring network (Belmecheri et al., 2016). Instrumental SWE was grafted onto the end of the reconstruction to allow comparison of recent with earlier SWE anomalies. Year 2015 was then identified as having the lowest SWE in the entire tree-ring record, although observed 2015 SWE fell within the 95% confidence interval of a few reconstructed years, notably in the 1500s.

Ideally, a long-term context for recent droughts would be derived from reconstructed values over the entire period, including the instrumental one (Biondi et al., 2002). This is often not feasible because tree-ring chronologies rarely extend as far as the most recent drought, hence the splicing of reconstructed and observed time series. Unfortunately, direct comparison of recent instrumental extremes with reconstructed values can be misleading because of the compression of variance inherent in regression. Accordingly, as was done by Griffin and Anchukaitis (2014) and Belmecheri et al. (2016), the instrumental extreme is interpreted probabilistically using the confidence band around the reconstruction to give a range of probable true values of the predictand given the reconstruction and its uncertainty.

Especially with time-nested reconstructions (e.g., Cook et al., 2004), the variance explained by the reconstruction may change over the length of the reconstruction. Hence, an additional step consisting of variance-scaling is sometimes taken to facilitate full-length comparison of anomalies. Such scaling, applied in the assessment of the recent California drought from PDSI by Griffin and Anchukaitis (2014), has the risk of overestimating the relative severity of past droughts. This is so because scaling amplifies the reconstructed departure from the mean, while for unexplained variance even the sign of the noise term is unknown. The expected direction of bias from this effect, however, is such that the conclusion about 2012–2014 being a less than one in a millennium event would be conservative rather than overstated.

The noise-added method we use is an alternative probabilistic approach that facilitates the objective estimation of the likelihood of events, such as multiyear unbroken sequences of dry years. Our results for the Carson River are consistent with the studies just mentioned in delineating the recent drought as unusually severe in a long-term context. Hydroclimate in all three regions is influenced to some degree by the same atmospheric circulation anomalies. Direct comparison of probabilities from the various studies is however pointless, because of differences in target reconstruction variables, choice of predictors, and reconstruction methods.

One of the most intriguing finding of Griffin and Anchukaitis (2014) was that warming exacerbated the recent drought. Warming also likely helps explain results of the simulations in which we tested for likelihood of the recent Carson River hydrologic drought arising from natural variability. Warming climate likely contributed to the 1960–2017 variability, yielding a low (though not zero) probability that the natural variability of flows for the earlier 1901–1959 interval could have yielded a drought with the intensity reached in 2012–2015 by chance alone. High interannual variability of flows makes assignment of significance difficult from short records, but even so the exact simulation suggests that the recent drought is outside the range of natural variability. On the other hand, the noise-added reconstructions indicate that we cannot conclude that the recent drought, as an event lasting four or more years, is unprecedented in intensity over the past 500 years. As with most natural time series, the likelihood of exceeding extremes increases with sample length. The observed flows are a snapshot, while the reconstructions are a panorama with an opportunity to capture unusual events even if the time series has stationary statistical properties. The conclusions from noise-added reconstructions would become less uncertain with greater accuracy of reconstruction. Here about 40% of the variance of Carson River flows cannot be explained by the tree-ring network. This percentage could perhaps be reduced greatly if the broadly regional tree-ring networks were augmented with drought-sensitive sites in key parts of the Carson watershed.

Alternative statistical reconstruction models as well as other types of tree-ring variables (e.g., subannual ring measurements) could also strengthen the flow signal. The apparent flattening out in the scatter of flow against tree-ring index toward low flows is an important nonlinearity that deserves further study. Such an effect could result when annual flows approach base flow, such that further response to precipitation decrease is not commensurate to the tree-growth response. A lowess-type modeling approach (e.g., Cleveland, 1979) would be another way to handle this effect but could be problematic when, as is the case here, a sharp change in slope is restricted to the lowest end of the scatterplot: the smoothing parameter may need to be so low that the fitted curve is too flexible—for example, not monotonically increasing over the full scatterplot.

Our reconstruction highlights the value of proxy records in giving a base period five times as long as the instrumental period for characterizing relative severity of dry and wet episodes. We emphasize, however, that updating old tree-ring records and developing new records from sites located in the study region, in combination with recent advances in producing km-level gridded reconstructions (Biondi, 2014) and in task-specific water-balance modeling (McCabe & Wolock, 2011; Saito et al., 2015), is expected to improve the quality of hydroclimatic reconstructions.

5. Conclusions

This work provided a multifaceted perspective on recent hydrologic drought in the Truckee/Carson Basin from a combination of tree-ring, climatic, and hydrologic data. Results indicated that the new millennium has been characterized by a shift toward longer duration reversals between drought and wetness. The striking 4-year sequence of dry years recorded in 2012–2015 has had an intensity unusual both in the context of natural variability of flows in first half of the 20th century and in 500 years of reconstructed flows using tree-ring records. Increasing air temperature has likely amplified the impact of recent precipitation departures on hydrology and tree growth. With 61% variance explained, our dendrochronological extension of Carson River streamflow is moderately accurate for a tree-ring reconstruction in the semiarid western United States. We also underscored the possible importance of nonlinear relationships for the dendrochronological assessment of drought severity. Here we adopted a two-segment piecewise reconstruction model to deal with an observed change in relationship at the lowest tree-ring index values. Assessments of water resource variability on long time scales for western U.S. rivers remain a useful tool for dealing with uncertainty under increasing pressure from climate change.

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