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FIVE HUNDRED YEARS OF HYDROLOGICAL DROUGHT IN THE UPPER COLORADO RIVER BASIN[1]

Janak Timilsena, Thomas C. Piechota, Hugo Hidalgo, and Glenn Tootle[2]

ABSTRACT: This article evaluates drought scenarios of the Upper Colorado River basin (UCRB) considering multiple drought variables for the past 500 years and positions the current drought in terms of the magnitude and frequency. Drought characteristics were developed considering water-year data of UCRB's streamflow, and basin-wide averages of the Palmer Hydrological Drought Index (PHDI) and the Palmer Z Index. Streamflow and drought indices were reconstructed for the last 500 years using a principal component regression model based on tree-ring data. The reconstructed streamflow showed higher variability as compared with reconstructed PHDI and reconstructed Palmer Z Index. The magnitude and severity of all droughts were obtained for the last 500 years for historical and reconstructed drought variables and ranked accordingly. The frequency of the current drought was obtained by considering two different drought frequency statistical approaches and three different methods of determining the beginning and end of the drought period (annual, 5-year moving, and ten year moving average). It was concluded that the current drought is the worst in the observed record period (1923-2004), but 6th to 14th largest in terms of magnitude and 1st to 12th considering severity in the past 500 years. Similarly, the current drought has a return period ranging from 37 to 103 years based on how the drought period was determined. It was concluded that if the 10-year moving average is used for defining the drought period, the current drought appears less severe in terms of magnitude and severity in the last 500 years compared with the results using 1- and 5-year averages.

(KEY TERMS: drought; streamflow; dendrochronology; planning; Palmer hydrological drought index; Palmer Z index; Upper Colorado River Basin.)

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INTRODUCTION

Hydrologic drought in the Colorado River Basin has been extensively studied by researchers using recorded streamflow and streamflow reconstructions from tree-ring data (e.g., Stockton and Jacoby, 1976; Meko *et al.*, 1995; Tarboton, 1995; Hidalgo *et al.*, 2000; Woodhouse *et al.*, 2006). Tree-ring growth (dendrochronology) can be used to extract various hydrological and climatic signals for periods in which little or no data exist. Typically, tree-ring growth is

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[2]Respectively (Timilsena, Piechota), Department of Civil and Environmental Engineering, University of Nevada, 4505 Maryland Parkway, Box 454015, Las Vegas, Nevada 89154-4015; Scripps Institution of Oceanography, Climate Research Division University of California, La Jolla, California 92037; and Department of Civil and Architectural Engineering, University of Wyoming, Dept. 3295, 1000 E. Univ. Ave., Laramie, Wyoming 82071 (E-Mail/Piechota: piechota@unlv.nevada.edu).

represented by various tree-ring data (e.g., ring width and the wood density). These tree-ring data allow researchers to formulate yearly time series relationships with streamflow and drought indices such as the Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Severity Index (PHDI) and Palmer "Z" Index (ZNDX). The current 5-year drought has persisted since the year 2000 in the Colorado River Basin of the southwestern United States and has received much attention. Major reservoirs such as Lake Powell and Lake Mead have lowered to approximately 50% of full reservoir capacity. Therefore, it is important to evaluate the magnitude of the current drought in relation to historical droughts using tree-ring data.

There are a variety of methods available to reconstruct hydroclimatic variables from tree-ring data. Stahle *et al.* (1998) used moisture sensitive tree-ring chronologies to reconstruct average July PHDI for tidewater and eastern Piedmont climatic division of Virginia and northern-central coastal plain divisions of North Carolina from 1185 to 1984 AD using a multiple linear regression model. Cook *et al.* (1999) reconstructed gridded summer PDSI from 1700 to 1978 AD using tree-ring chronologies by using the Point by Point Regression (PPR) technique. Cook *et al.* (1999) defined the PPR technique as the sequential, automated fitting of a single point principle components regression model to determine the gridded pattern of PDSI. Woodhouse (2001) reconstructed the streamflow from 1703 to 1987 AD for Middle Boulder Creek in the Colorado front range using the stepwise regression method. In addition, Woodhouse (2003) reconstructed April 1 snow water equivalent (SWE) for the Gunnison river basin region in western Colorado from 1569 to 1999 AD considering tree-ring chronologies using the stepwise regression technique. Gedalof *et al.* (2004) reconstructed Columbia river water-year streamflow since 1750 AD considering tree-ring chronologies using a principle component regression model.

The relationships between tree ring and drought variables are typically developed through the use of principal component analysis (PCA) regression model procedures (e.g., Fritts, 1991; Hidalgo *et al.*, 2000). In the Hidalgo *et al.* (2000) study, many PCA regression models corresponding to different subsets of predictors (tree-ring variables) were compared based on the cross validation standard error (CVSE), and the model with the lowest CVSE was selected to reconstruct the hydrologic variables. The improved models (lower CVSE) were composed of fewer variables than the full model (using all tree-ring variables available), and had smaller error and better fit; however, it was found that the procedure results in models that are biased towards dry periods. Using the procedures of Hidalgo *et al.* (2000), Piechota *et al.* (2004) evaluated streamflow data from two stations and a hydrologic index to determine the ranking of the current drought in the Colorado River basin.

Methods are also available for determining drought risks in terms of return period using historical and reconstructed streamflow. Tarboton (1995) assessed the risk of drought and developed drought scenarios in the southwestern U.S. based on unimpaired streamflow and tree-ring reconstructed streamflow. Frequency analysis was performed using four different methods to estimate the return period and risk associated with the different drought scenarios. Loaiciga (2005) introduced a compound renewal model for the probabilistic analysis of multiyear drought recurrence. The drought duration and interarrival time were considered to be a Poisson process. The sum of interarrival time and subsequent drought duration was defined as the renewal time.

In this article, five hydrologic parameters were reconstructed using the procedures of Hidalgo *et al.* (2000) for 500 year period in the UCRB: water-year (October through September) streamflow volume at two stations within the UCRB; Lee's Ferry streamflow data; and the PHDI and ZNDX for the UCRB climate divisions. Droughts were quantified and ranked considering magnitude, severity and duration. Further, frequency analysis using two different methods was performed to obtain the return period of the current drought using magnitude and duration of multiple drought variables under three different scenarios of moving averages. The first contribution of this research is the reconstruction of multiple drought variables; three streamflow stations (Cisco, Green and Lee's Ferry) and two drought indices (PHDI and ZNDX). The second contribution is characterizing the drought in terms of magnitude, severity and frequency for multiple drought variables since different variables and different methods can yield different results in terms of drought ranking and return periods. Finally, the measures of drought (magnitude, severity and frequency) were evaluated using three different procedures for determining the drought periods over the past 500 years. This study builds on the work of Piechota *et al.* (2004) in three main areas. First, additional hydrologic variables (Lee's Ferry and the ZNDX) were reconstructed to further evaluate the sensitivity of drought measures. Second, the sensitivity of the procedures for determining the drought period based on different length moving averages was evaluated. And third, the return periods of different drought periods were determined using two different approaches. The Piechota *et al.* (2004) study only evaluated the ranking of the different drought periods and did not define the return periods.

BACKGROUND DATA

Upper Colorado River Basin (UCRB) Description

The Upper Colorado River Basin drains an area of more than 279,720 square kilometers, with major tributaries including the Green, Gunnison and San Juan rivers (Colorado River Water User's Association, CRWUA). It is the primary surface water producer for the lower Colorado River because of spring-summer snowmelt runoff. The river generates electrical power of 12.2 trillion kWh, and is the main water supply for 25 million people within the basin states and adjoining areas. More than 5,670 square kilometers of irrigated land throughout the Colorado River basin produce about 15% of the nation's crops, 13% of its livestock, and agricultural benefits of more than US$1.5 billion a year (CRWUA). The UCRB consists of mountains, forests, agriculture, and low-density development that extends through five states and terminates at Lee's Ferry, just downstream from Glen Canyon Dam in northern Arizona. The "Law of the River" governs the amount of water supplied to each state in the Colorado River basin; however, many states, including California, depend on water surpluses (water amounts that exceed their legal allocations) to keep up with the demand of a growing population and agricultural industry.

Streamflow Data

Average monthly streamflow data of the Colorado River near Cisco, Utah (USGS Station #09180500) and the Green River near Green river, Utah (USGS Stations #09315000) (Figure 1) were obtained in cubic feet per second from 1923 to 2004 (82 years) from the U.S. Geological Survey (USGS), NWIS web site (http://nwis.waterdata.usgs./gov/usa/nwis/monthly). Based on the historical record, the average water-year (October through September) streamflow volume for Cisco station of the Colorado River (referred to as Cisco) and Green river station streamflow (referred to as Green) were 6.31 and 5.05 km^3 respectively. The data for Cisco and the Green stations have minor diversions for agricultural and domestic water use; however, these index sites are considered to generally reflect hydrologic conditions in their respective watersheds, including snowpack and amount of water stored in reservoirs (USGS, U.S., Geological, Survey). It is also noteworthy that the changes in water demand from water users in the upper and lower Colorado River basin are not considered in this study. This is considered to be insignificant since the stations are located in the headwaters of the watershed and also changes because of the development in the upper basin are relatively minor compared with the magnitude of the flows.

The monthly flow rate was averaged for the water-year and converted to an annual volume (km^3). Similarly, reconstructed (1493-1895) and observed stream flow data (1896-1962) at Lee's Ferry station (referred to as Lee's Ferry) were obtained from the U.S Bureau of Reclamation. Because of construction of Glenn Canyon dam in 1962, the Lee's Ferry's streamflow data from 1963 was impaired. In order to get the unimpaired flow at Lee's Ferry for the period 1963-2004, a linear regression equation derived by Webb *et al.* (2004) based on sum of flow volumes of the principal rivers into Lake Powell was utilized:

$$Q_{\mathrm{LF}} = 1.044\,Q_{\mathrm{in}} - 0.1688 \tag{1}$$

where, Q_{LF} is the annual flow volume at Lee's Ferry in million acre-feet and Q_{in} is the annual inflows to Lake Powell in million acre-feet. Although it is difficult to determine the accuracy of the Lee's Ferry streamflow record after such adjustment, this station was selected so as to compare the results of this reconstruction with the previous reconstruction by Stockton and Jacoby (1976).

Drought Indices

The Palmer Drought Severity Index (PDSI) was originally developed by Palmer in 1965 for semi-arid regions (Palmer, 1965). It is based on a weekly (or monthly) water balance for a generic, two layer soil strata. Similar to the PDSI, the PHDI and ZNDX values are dimensionless and typically vary between −4 (indicating a severe shortage of water) and + 4 (indicating a large surplus of water). The PHDI is a hydrological index of the severity of a wet or dry period where monthly PHDI values are calculated in a similar fashion as the PDSI. However, in the PHDI calculation the criterion for the elimination of a dry spell (or wet spell) is more stringent than the PDSI. The PHDI considers a drought to have ended when the moisture deficit actually vanishes while the PDSI considers a drought to have ended when moisture conditions begin an uninterrupted rise in the index that ultimately erases the water deficit.

The ZNDX is an intermediate value in the computation of the PDSI that represents the moisture anomaly for the current period without considering antecedent conditions. The ZNDX is useful for

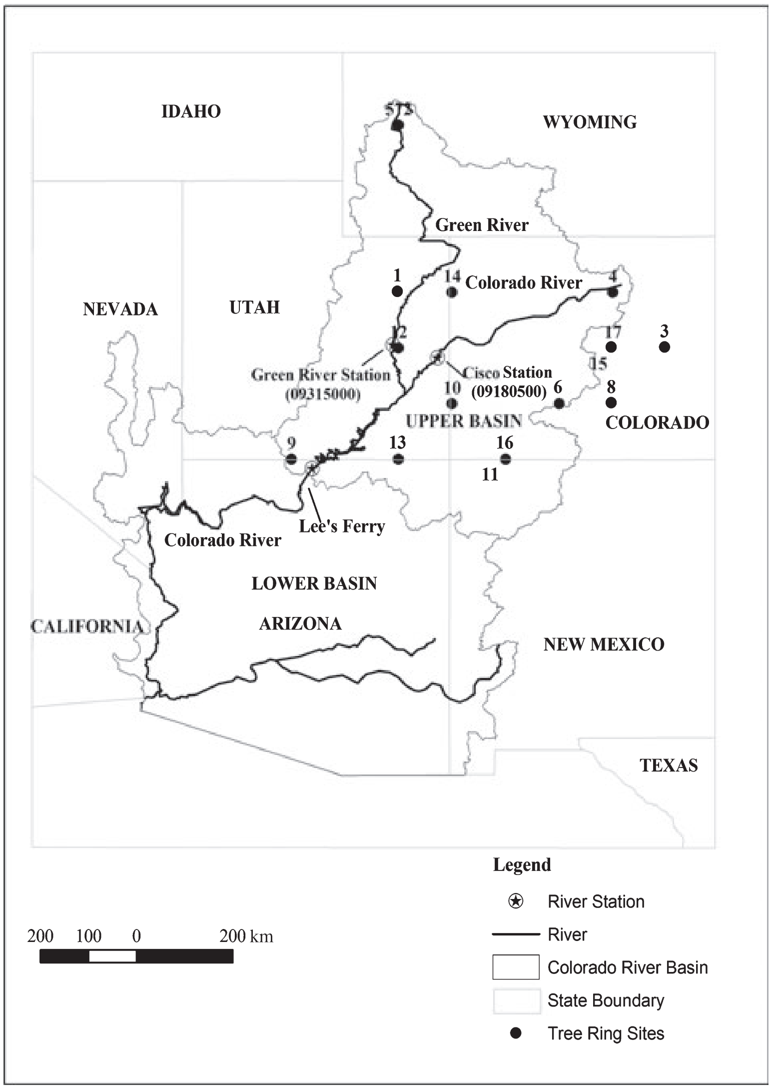

FIGURE 1. Location Map of the Upper Colorado River Basin With Tree Ring Sites (1-17) and Streamflow (Cisco, Green, and Lee's Ferry) Station Locations.

monitoring agriculture drought, as it responds quickly to changes in soil moisture values (Keyantash and Dracup, 2002) and reflects the departure of average moisture for a particular period (Heim, 2002).

The UCRB contains five climate divisions; Colorado Division-2, Wyoming Division-3, Utah Division-5, Utah Division-6 and Utah Division-7. The PHDI and ZNDX of each climate division contained in the UCRB were utilized in this study. These data were obtained from the National Climatic Data Center (NCDC) (http://www1.ncdc.noaa.gov/pub/data/cirs/) (NCDC, 2004a,b). The monthly drought indices were averaged for the water-year (October through September) for each climate division and averaged for all five climate regions contained in the UCRB in order to find a representative water-year time series of the whole basin.

Tree-Ring Data

The tree-ring data of 17 representative chronologies for the UCRB used for this study were selected according to Hidalgo *et al.* (2000) (see Figure 1). These chronologies were originally obtained from NOAA's International Tree Ring Data Bank (http://www.ngdc.noaa.gov/paleo/treering.html), and are composed of standardized chronologies representing tree growth throughout the UCRB in the states of Colorado

TABLE 1. Summary of the Tree-Ring Chronologies Used in This Study.

Site Number	Site Name	Location	Year	Identification Number	SPID	Elevation (m)
1	Unita Mountains A	Utah	1972	277550	PCEN	3353
2	Gros Ventre	Wyoming	1972	316597	PIFL	2179
3	Chicago Creek	Colorado	1965	115549	PSME	2835
4	New North Park	Colorado	1965	110549	PSME	2469
5	Uhl Hill	Wyoming	1972	318599	PIFL	2225
6	Black Canyon	Colorado	1965	117549	PSME	2426
7	Wind River Mountains D	Wyoming	1972	283590	PIFL	2500
8	Upper Gunnison	Colorado	1965	116549	PSME	2530
9	Mammoth Creek	Utah	1990	MAM519	PILO	2590
10	La Sal Mountains A	Utah	1972	285620	PIED	2323
11	Bobcat Canyon	Colorado	1972	61099	PSME	2042
12	Nine Mile Canyon	Utah	1965	123549	PSME	1920
13	Navajo Mountain	Utah	1972	133099	PIED	2286
14	Unita Mountains D	Utah	1972	280620	PIED	2289
15	Eagle	Colorado	1965	112549	PSME	1951
16	Sch. Old Tree 1	Colorado	1964	640106	PSME	2103
17	Eagle East	Colorado	1965	113629	PIED	2164

The year column corresponds to the year when the chronology was sampled. SPID refers to tree species: PCEN, *Picea engelmannii*; PIFL, *Pinus flexilis*; PSME, *Pseudotsuga menziesii*; PILO, *Pinus longaeva*; PIED, *Pinus edilus*, Elev refers to elvation in meters above sea level. (from Hidalgo *et al.*, 2000).

(eight species), Utah (six species) and Wyoming (three species). A summary of the characteristics of each chronology is presented in Table 1.

METHODS

Reconstruction Method of Hydrologic Drought Variables

As noted earlier, the procedures of Hidalgo *et al.* (2000) were utilized in this study. Following is a summary of these procedures. Multiple reconstruction models corresponding to different subsets of predictors (tree-ring variables) were evaluated and ranked according to their cross validation standard error (CVSE). Each individual reconstruction model was based on a PCA-regression model. The PCA methodology was used to transform the linear combinations of the original variables into a new set of independent variables or PCs because the tree-ring chronologies were interrelated. After the truncation of the significant PCs, the leading PCs were included in order one-by-one in the final regression model. Each time a PC was included a *t*-test and "sign-test" were used as the criteria for retaining the added PC in the regression equation. The *t*-test was used to test the significance of the coefficient of the PC in the regression equation and the sign-test was passed if the algebraic signs of the regression coefficient of the PCs expressed in terms of the original variables matched the algebraic sign of the partial correlation coefficient of the original variable (each tree-ring site) with each dependent variable (streamflow at each location or the drought indexes).

The model calibration and verification were performed using cross validation and the skill score of the CVSE. The CVSE was used by Garen (1992) to select the best predictive models and is defined as

$$\mathrm{CVSE} = \sqrt{\frac{\sum\left(y_i - \hat{y}_{(i)}\right)^2}{n-p}} \tag{2}$$

where y_i is the observed streamflow for year i. $\hat{y}_i$ is the fitted response of the ith year computed from the fit with the ith observation removed, n is the number of years in the data set, and p is the number of regression coefficients.

Testing all possible combinations of subsets of tree-ring sites would be computationally very intensive. For this reason, a procedure for selecting the subsets to be evaluated was developed. In order to find the best predictor subsets, the model first found the lowest CVSE for each predictor independently. Next, the lowest CVSE for two variables combination was found. The procedure continued adding variables one by one until the total number of variables were used. If the minimum CVSE for combinations with an added variable was larger than the previous minimum CVSE, the process was stopped and the extra variable was not included. The procedure of selecting subsets of predictors may not find the global optimum of all combinations of variables, but it gives parsimonious model that is shown to perform better than the model using all the variables (Hidalgo *et al.*, 2000).

For each reconstruction, more than 16,000 possible models corresponding to multiple subsets of tree-ring predictors were evaluated for each dependent variable and ranked according to CVSE. The calibration period for Cisco, Green, Lee's Ferry, PHDI, and ZNDX were 1924-62, 1924-62, 1897-1962, 1897-1962 and 1897-1962, respectively.

The skill of the model was determined using several measures. The reduction of error (RE) statistic provides a sensitive measure of reliability and contains three components: RISK, BIAS, and COVAR (Fritts, 1991), and ranges in magnitude from negative infinity (infinity error) to 1.0 (perfect estimation). RISK is always negative (ideally, RISK = −1) and its absolute magnitude is a comparative measure of the variability of both the estimates and actual observations used in testing (Fritts, 1991). BIAS can be positive or negative and is positive if a shift in the mean of the independent sample from calibration is reproduced in the estimates (Fritts, 1991). Similarly, the COVAR term reflects the strength of the correlation between the estimated and observed data and measures the similarity of the temporal patterns in the estimates and observations (Fritts, 1991). The RE is typically obtained utilizing independent datasets to evaluate the strength of the association between observed values and reconstructed values. But in this model, the CVSE was used on calibration and verification periods to independently test the model. The RE was based on the entire period of record. Since the model is based on the minimum CVSE, the RE statistic is used to compare the performance of different drought variables. The coefficient of determination (R^2) indicates the explained variance considered by the model (Fritts, 1991). R^2 indicates the fraction of variance recovered during the reconstruction from the original variance of the predictand variables.

Drought Identification Method

Hydrologic drought is typically defined as consecutive series of years during which the average annual drought variable is continuously below some specified threshold, such as the long-term mean (Dracup *et al.*, 1980). In this study, the long-term mean was assumed to be the threshold. Hydrologic drought was characterized by duration (years), magnitude (the cumulative deficit below the threshold for consecutive years), severity (average deficit below the thresholds) and frequency for each drought variable.

The first step in the analysis was to define periods of drought. As mentioned previously, drought was defined as the cumulative deficit relative to long-term mean. The long-term mean (threshold) was obtained first by taking the average of the adjoined historical and reconstructed data of the drought variable. Then, anomalies with respect to the long-term mean were obtained by subtracting the long-term mean from the annual value of the hydrologic variable (e.g., streamflow quantity for the year). After obtaining the anomalies of each drought variable, droughts were defined as the consecutive negative anomalies for at least 2 years. The magnitude was obtained by adding up all the anomalies during the drought. The duration was defined as the elapsed time between the first year with a negative anomaly and the last year with a negative anomaly. Lastly, the severity was obtained by dividing the drought magnitude by the drought duration. This analysis is termed Drought Identification Method "1."

The procedure summarized above prevents the identification of a drought period that may have a year(s) with a positive anomaly. To investigate the occurrence of longer term droughts that may have one or more positive anomaly years in the period, a procedure (Drought Identification Method "5") was developed where the drought period was determined based on the moving average of the hydrologic variable. In this procedure, the 5-year moving average was first determined for the anomaly of the hydrologic variable. Then, the beginning of the drought was identified as the year when the 5-year moving average was negative and the end of the drought was identified when the 5-year moving average returned to a positive value. This defined the drought duration. Using this defined period of drought based on the moving average, the magnitude was obtained by adding up all the annual anomalies during the drought. Similar to the earlier analysis using annual data, the severity was obtained by dividing the drought magnitude by the drought duration. This same procedure was repeated for the case where the 10-year moving average was used as a basis for determining the drought period (Drought Identification Method "10"). Figure 2 illustrates the differences between the drought identification methods for the Cisco streamflow station and for a severe drought in the late 1500s. In addition, the drought duration is noted and the corresponding annual anomalies used to compute the drought magnitude are shown.

Drought Frequency

The determination of the frequency of droughts was considered using two different approaches: (1) ranking approach; and (2) renewal method considering magnitude and duration simultaneously. A brief description of the approaches is provided below.

In the ranking approach, the droughts were ranked according to the magnitude. Then, the corres-

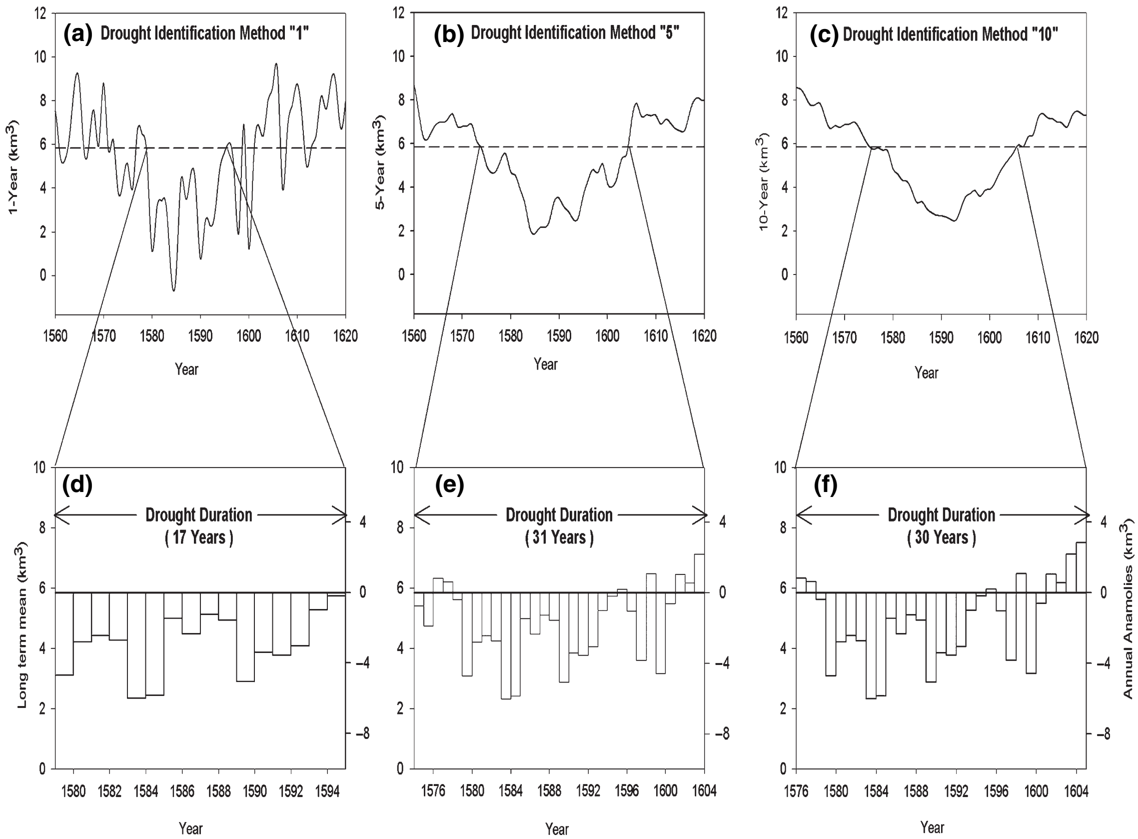

FIGURE 2. Adjusted Reconstructed Cisco Station Streamflow for the Most Severe Drought (end of 15th century) Identification: (a) Annual Water-Year; (b) 5 Year Moving Average; (c) 10 Year Moving Average Streamflow; (d) Drought Duration and Corresponding Annual Anomalies Defined by the Drought Identification Method "1" ; (e) Drought Duration and Corresponding Annual Anomalies Defined by the Drought Identification Method "5" ; (f) Drought Duration and Corresponding Annual Anomalies Defined by the Drought Identification Method "10". Streamflow is shown in solid line; dashed horizontal line in (a), (b), and (c) represents the long-term water-year mean; horizontal straight line in (d), (e), and (f) represents the long-term water-year mean; and vertical bar represents annual anomalies.

ponding probability (p) and return period (R) were determined based on the Weibull distribution:

$$p = \frac{m}{(N+1)} \tag{3}$$

$$R = \frac{1}{P} \tag{4}$$

where m is a rank (largest drought receiving rank 1) and N is the total number of years of data.

The second approach was a compound renewal approach (Loaiciga, 2005) considering both magnitude and duration. The current drought magnitude and duration were considered as a threshold. Droughts of higher or equal to the current drought in terms of magnitude and duration simultaneously were only considered to obtain the average drought duration and average interarrival time of droughts. The expected value of the renewal time ($\bar{R}$) is equal to the sum of expected value of duration (D) and the expected value of interarrival time (T), or

$$\bar{R} = \theta + \frac{1}{a_1} + \frac{1}{a_2} \tag{5}$$

where, the shape parameters are

$$a_1 = \frac{1}{(\bar{D} - \theta)} \tag{6}$$

$$a_2 = \frac{1}{\bar{T}} \tag{7}$$

and the parameters $\bar{D}$ and $\bar{T}$ are the respective sample average of drought duration ($\bar{D}$) and the sample average of interarrival time ($\bar{T}$) considering all the droughts of the past 500 years, which are at least equal or greater than the current drought magnitude and duration simultaneously. The threshold θ, is the current drought duration in this analysis.

RESULTS

Reconstruction of Hydrologic Variables

Table 2 presents a summary of the common reconstruction performance statistics. For reconstruction of the Cisco, Green, and Lee's Ferry, RE values were 0.97, 0.98, and 0.98, and the coefficient of determination (R^2) values were 0.72, 0.74, and 0.82, respectively. Similarly for the PHDI, RE and R^2-value were 0.69 and 0.69, respectively. Lastly, the RE and R^2-values for the Palmer Z index were 0.57 and 0.57, respectively. The summary of statistics shown in Table 2 indicates a good relationship between the hydrologic variables and the tree-ring data, with streamflow having the strongest relationship with the tree-ring data. The R^2-values were less in the case of PHDI and ZNDX as compared with streamflows.

TABLE 2. Performance Statistics and Error Characteristics of the Reconstructions Models for Multiple Drought Variables.

Performance Statistics	Cisco	Green	Lee's Ferry	PHDI	ZNX
R^2	0.72	0.74	0.82	0.69	0.57
CVSE (km^3/yr)	0.19	0.14	2.34	0.15	0.07

R^2 is the coefficient of determination. CVSE is the cross-validation standard error in km^3/water-year for streamflow and units/water-year for PHDI and ZNDX.

The difference in variability between the observed and reconstructed drought variables made it difficult to adjoin the two time series. In order to get a closer match, the reconstructions with the observations, the reconstructed drought variables were rescaled to the observed variance using the following equation:

$$\hat{x}_i^* = \left(\frac{\hat{x}_i - \hat{\bar{x}}}{\hat{\sigma}}\right)\sigma + \hat{\bar{x}} \tag{8}$$

where, $\hat{x}_i$ is the original reconstructed variable, $\hat{\bar{x}}$ and $\hat{\sigma}$ are the reconstructed mean and standard deviation, σ is the historical (observed) standard deviation, and $\hat{x}_i^*$ is the adjusted reconstructed variable. This adjustment was performed for all the reconstructed five drought variables. Equation (8) was utilized to statistically improve the reconstructed data in terms of variance based on the observed variance before adjoining two time series (i.e., reconstructed and observed). Though with this equation, the variance of the reconstructed data was improved, there are other factors associated with the tree growth such as detrending, autocorrelation and biological effects which have not been addressed in this analysis. Further analysis of the magnitude and frequency was performed based on the rescaled (adjusted) reconstructed values and historical (observed) drought variables.

For the drought identification and frequency analysis, the time series water-year data of five drought variables (Cisco, Green, Lee's Ferry, PHDI, and ZNDX) from 1493 to 2004 were used. In order to obtain Cisco and Green water-year time series from 1493 to 2004, adjusted (as noted above) reconstructed data series (1493-1922) were combined with observed historical data series (1923-2004). Similarly, Lee's Ferry water-year time series from 1493 to 2004 was obtained by combining adjusted reconstructed data (1493-1895), observed unimpaired data (1896-1962) and regressed data (1963-2004). PHDI and ZNDX water-year time series from 1493-2004 were obtained by adjoining respective adjusted reconstructed data (1493-1895) and observed historical data (1896-2004).

Drought Identification

The available historical and adjusted reconstructed data from 1493-2004 of five different drought variables (Cisco station streamflow, Green River streamflow, Lee's Ferry streamflow, PHDI and ZNDX) were used to characterize droughts using the three different methods for drought identification. In Figure 3, it is noteworthy that the long-term mean of the PHDI and ZNDX are negative. This is consistent with Tarboton (1995), who observed that the observed mean was higher (wet) than the reconstructed mean for drought variables. Since the Palmer drought indexes were developed to interpret 20th Century variations; the negative mean suggests that the period of 1500s through the 1800s was much drier than the historical record from the early 1900s. Although the observational period presents one of the wettest period on record and therefore the reconstructed mean of the Palmer indexes would tend to be negative, it is known also that tree-ring chronologies from this region generally tend to present a bias towards the dry periods since tree-ring growth is more responsive to hot-dry than cool-moist extreme conditions (Hidalgo *et al.*, 2001).

Figures 3-5 present the duration (width of bar) and magnitude (height of bar) of droughts for the three different methods (Drought Identification Methods 1,

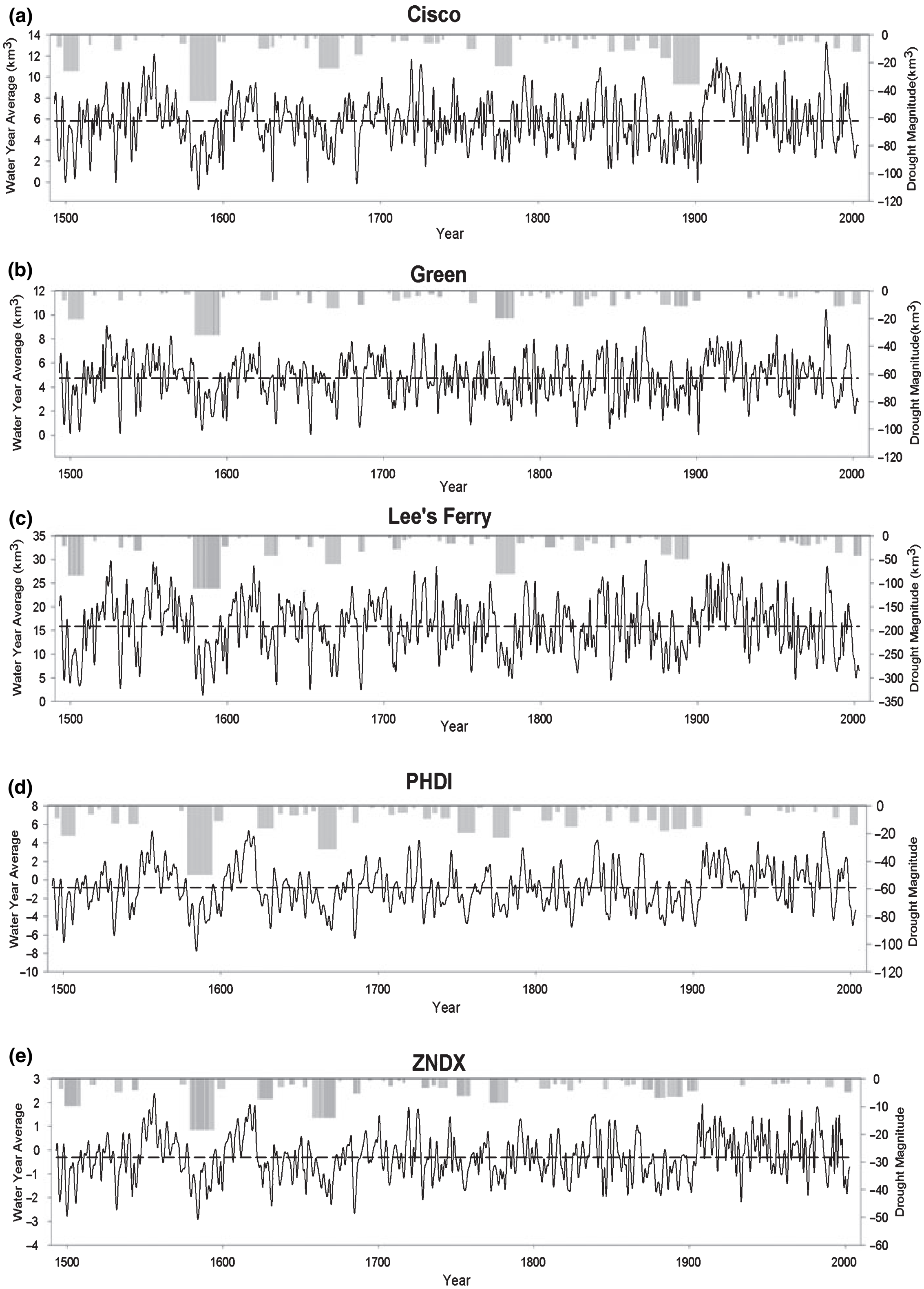

FIGURE 3. Drought Magnitude and Duration (vertical bars) for Drought Identification Method "1" of Adjusted Reconstructed Plus Observed Annual Water-Year Data of Multiple Drought Variables, (a) Cisco (streamflow), (b) Green (streamflow), (c) Lee's Ferry (streamflow), (d) PHDI, and (e) ZNDX. The solid line represents the annual water-year data of drought variables. The dashed horizontal line indicates the long-term water-year mean of the drought variables.

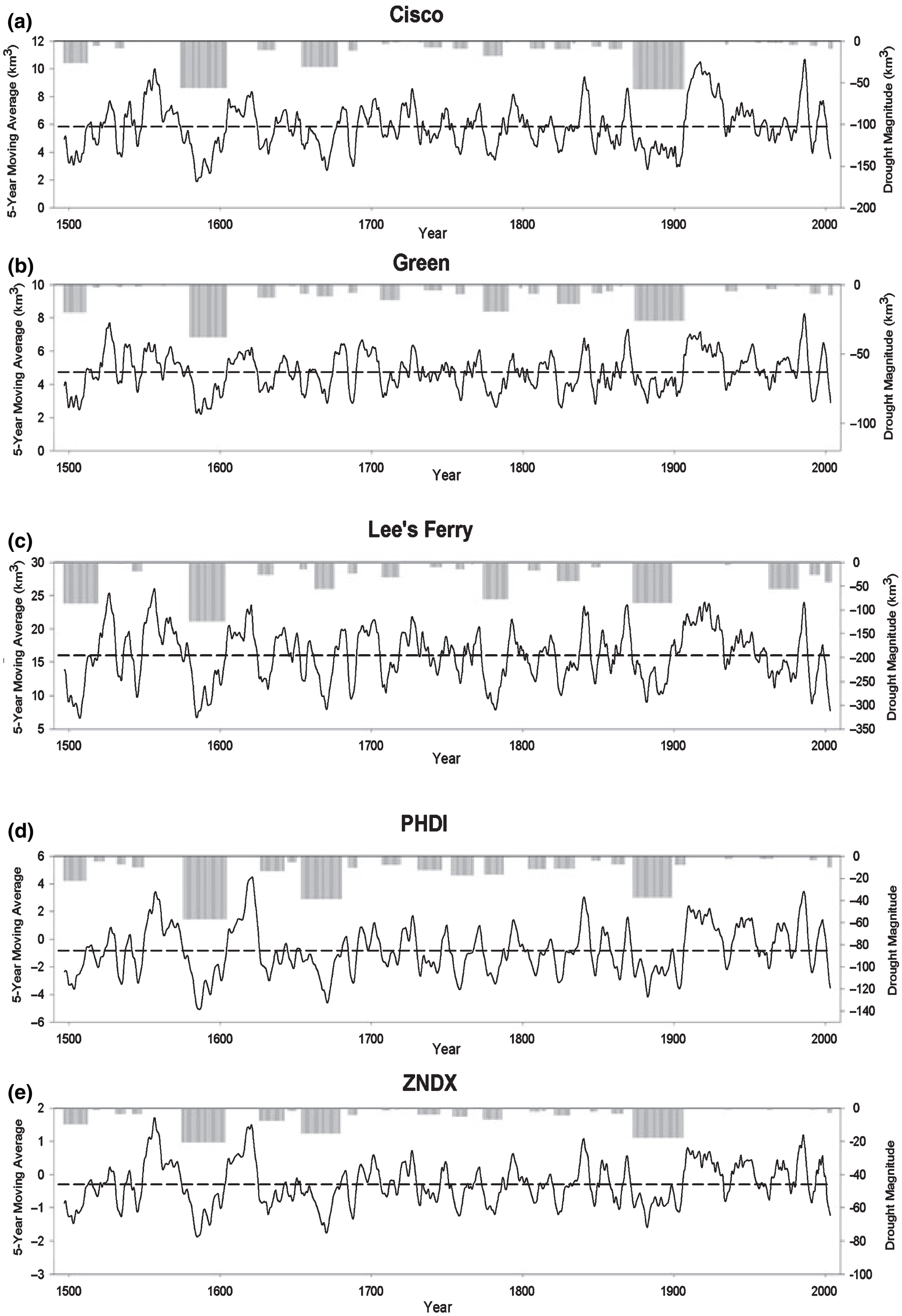

FIGURE 4. Drought Magnitude and Duration (vertical bars) for Drought Identification Method "5" of Adjusted Reconstructed Plus Observed Water-Year Data of Multiple Drought Variables, (a) Cisco (streamflow), (b) Green (streamflow), (c) Lee's Ferry (streamflow), (d) PHDI, and (e) ZNDX. The solid line represents the 5-year moving average water-year data of the drought variables. The dashed horizontal line indicates the long-term water-year mean of the drought variables.

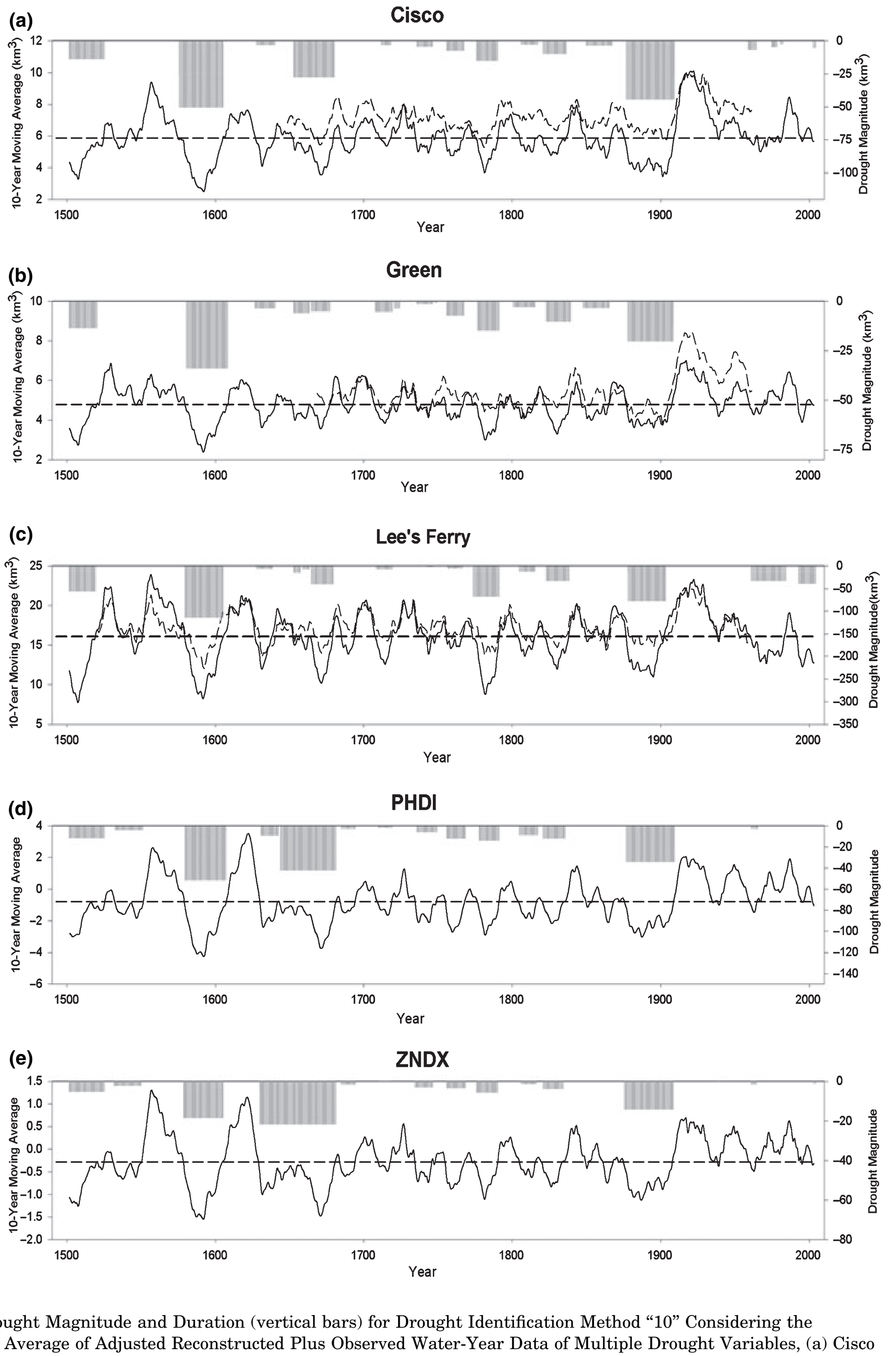

FIGURE 5. Drought Magnitude and Duration (vertical bars) for Drought Identification Method "10" Considering the 10-year Moving Average of Adjusted Reconstructed Plus Observed Water-Year Data of Multiple Drought Variables, (a) Cisco (streamflow), (b) Green (streamflow), (c) Lee's Ferry (streamflow), (d) PHDI, and (e) ZNDX. The solid line represents the 10-year moving average water-year data of the drought variables. The long dashed horizontal line indicates the long-term water-year mean of drought variables. The thin short dash curve indicates the 10-year moving average by Stockton and Jacoby (1976).

TABLE 3. Drought Ranking Considering the Magnitude of Multiple Drought Variables for the Three Different Drought Identification Methods.

Drought Variables	Drought Identification Method	Rank # 1	Rank # 2	Rank # 3	Rank # 4	Rank # 5	Current Drought Rank
Cisco	1	1579-95	1886-1902	1499-1508	1661-73	1773-83	#8 (2000-2004)
	5	1873-1906	1574-1604	1654-77	1497-1512	1774-86	#12 (2002-2004)
	10	1576-1605	1877-1909	1653-80	1776-90	1502-25	#9 (2003-2004)
Green	1	1580-95	1499-1508	1772-83	1664-71	1886-94	#11 (2000-2004)
	5	1580-1604	1874-1906	1497-1511	1774-90	1823-37	#9 (2002-2004)
	10	1581-1608	1878-1908	1777-91	1502-20	1823-39	No drought
Lee's Ferry	1	1579-95	1499-1508	1772-83	1663-72	1886-94	#7 (2000-2004)
	5	1580-1603	1497-1519	1873-98	1774-90	1963-82	#7 (2000-2004)
	10	1580-1605	1878-1903	1774-91	1502-19	1665-79	#6 (1993-2004)
PHDI	1	1579-94	1662-73	1773-83	1499-1507	1751-61	#11 (2000-2004)
	5	1576-1604	1654-80	1873-98	1497-1511	1753-67	#13 (2002-2004)
	10	1580-1607	1644-81	1877-1909	1778-91	1756-68	No drought
ZNDX	1	1579-94	1658-72	1499-08	1772-83	1623-32	#11 (2000-2004)
	5	1575-1603	1873-1906	1654-79	1497-1512	1626-42	#14 (2002-2004)
	10	1630-81	1579-1605	1876-1908	1776-90	1502-25	#13 (2003-2004)

This ranking summary is based on the time series water-year data of adjusted reconstructed plus historical drought variables.

TABLE 4. Drought Ranking Considering the Severity of Multiple Drought Variables for the Three Different Drought Identification Methods.

Drought Indices	Drought Identification Method	Rank # 1	Rank # 2	Rank # 3	Rank # 4	Rank # 5	Current Drought Rank
Cisco	1	1631-1632	1515-1516	1652-54	1845-48	1684-88	#12 (2000-2004)
	5	2002-2004	1685-90	1574-1604	1873-1906	1497-1512	#1 (2002-2004)
	10	2003-2004	1576-1605	1877-1909	1975-78	1981-82	#1 (2003-2004)
Green	1	1652-54	1845-48	1684-87	1495-97	1597-98	#11 (2000-2004)
	5	2002-2004	1580-1604	1497-1511	1798-99	1774-90	#1 (2002-2004)
	10	1581-1608	1878-1908	1777-91	1502-20	1823-39	No drought
Lee's Ferry	1	1845-47	1684-87	1499-1508	2000-2004	1963-64	#4 (2000-2004)
	5	2000-2004	1580-1603	1774-90	1663-75	1685-90	#1 (2000-2004)
	10	1580-1605	1774-91	1993-2004	1502-19	1878-1903	#3 (1993-2004)
PHDI	1	1579-94	1879-84	1684-87	1495-97	1845-48	#6 (2000-2004)
	5	2002-2004	1576-1604	1685-90	1497-1511	1654-80	#1 (2002-2004)
	10	1580-1607	1644-81	1877-1909	1778-91	1756-68	No drought
ZNDX	1	1845-47	1495-97	1597-94	1822-25	1684-88	#11 (2000-2004)
	5	2002-2004	1575-1603	1685-90	1497-1512	1654-79	#1 (2002-2004)
	10	1579-1605	2003-2004	1876-1908	1630-81	1776-90	#2 (2003–2004)

This ranking summary is based on the time series water-year data of adjusted reconstructed plus historical drought variables.

5, and 10). The ranking of the droughts and position of the current drought in terms of magnitude and severity are presented in Tables 3 and 4, respectively. Following is a summary of the results for each drought identification method.

Drought Identification Method "1"

Figure 3 summarizes the droughts identified based on annual water-year data. During the analysis of annual water-year data, Cisco indicated 52 droughts with the highest magnitude of 47.86 km^3 and lowest of 0.78 km^3 (Figure 3a). Green indicated 51 droughts with the highest magnitude of 32.06 km^3 and lowest of 0.41 km^3 (Figure 3b). Lee's Ferry indicated 52 droughts with the highest and lowest magnitude of 110.32 km^3 and 1.34 km^3 (Figure 3c). The PHDI indicated 52 droughts with the highest and lowest magnitude of 49.63 and 0.42 (Figure 3d). The ZNDX indicated 46 droughts with the highest magnitude of 18.43 and 0.48 (Figure 3e).

Considering severity, Cisco yielded the highest severity of 4.24 km^3/year during 1631-32 and lowest of 0.27 km^3/year during 1694-96. Green yielded the highest severity of 2.78 km^3/year during 1652-54 and lowest of 0.21 km^3/year during 1658-59. Lee's Ferry indicated the highest and lowest severity of 8.60 km^3/year and 0.67 km^3/year during 1845-47 and 1558-59 respectively. The PHDI indicated the highest severity of 3.1/year during 1579-94 and lowest severity of 0.21/year during 1679-80. The ZNDX indicated the highest severity of 1.24 /year during 1845-47 and lowest severity of 0.16 during 1694-96.

The current drought (2000-04) ranked as the 7th to 11th worst drought considering magnitude for the Cisco, Green, Lee's Ferry, PHDI and ZNDX in the past 500 plus years of record (Figure 3 and Table 3). The largest drought occurred during the late 1500s and this was consistent for all streamflow stations, PHDI and ZNDX. The magnitude of the late 1500s drought was significantly greater than the current drought (3-5 times greater, depending upon the drought variable selected). Similarly, the current drought (2000-04) ranked as the 4th to 12th worst in terms of severity for Cisco, Green, Lee's Ferry, PHDI, and ZNDX (Table 4).

Drought Identification Method "5"

Figure 4 summarizes the drought periods identified based on the 5-year moving average and the drought magnitude and severity based on the annual anomalies. For Cisco, 27 droughts of highest magnitude of 57.57 km^3 and lowest magnitude 0.30 km^3 (Figure 4a) were identified. The Green indicated 29 droughts with the highest and lowest magnitude of 37.97 and 0.13 km^3 (Figure 4b). Lee's Ferry indicated 21 droughts with the highest magnitude of 124.17 km^3 and lowest magnitude of 2.60 km^3 (Figure 4c). The PHDI index indicated 24 droughts with the highest and lowest magnitude of 56.87 and 0.42 (Figure 4d). Similarly, the ZNDX indicated 26 numbers of droughts with the highest and lowest magnitude of 20.41 and 0.11 (Figure 4e). The current drought (2002-04) ranked 7th to 14th worst drought in terms of magnitude considering all the drought variables. The largest droughts occurred during the late 1500s (Green, Lee's Ferry, PHDI, and ZNDX) and late 1800s (Cisco). The magnitudes of the largest droughts were 2-8 times higher than the current drought depending upon the drought variables (Table 3).

Cisco yielded the highest severity of 2.90 km^3/year during 2002-04 and the lowest of 0.07 km^3/year during 1646-49. Green yielded the highest severity of 2.37 km^3/year during 2002-04 and lowest of 0.06 km^3/year during 1801-02. Lee's Ferry indicated the highest and lowest severity of 8.29 km^3/year and 0.52 km^3/year during 2000-04 and 1532-36, respectively. The PHDI indicated the highest severity of 3.28/year during 2002-04 and lowest severity of 0.14/year during 1789-91. The ZNDX indicated the highest severity of 0.88 /year during 2002-04 and lowest severity of 0.05/year during 1789-90. The current drought (2002-04) ranked as the worst in terms of severity for the Cisco, Green, Lee's Ferry, PHDI, and ZNDX in the past 500 years of record (Table 4).

Drought Identification Method "10"

Figure 5 summarizes the drought periods identified based on the 10-year moving average and the drought magnitude and severity based on the annual anomalies. In this case, Cisco indicated 16 droughts with the highest magnitude of 50.48 km^3 and 2.27 km^3 (Figure 5a). Green indicated 17 droughts with the highest and lowest magnitude of 33.82 and 0.05 km^3 (Figure 5b). Lee's Ferry indicated 16 droughts with the highest and lowest magnitude of 113.55 and 0.56 km^3 (Figure 5c). PHDI indicated 14 droughts with the highest and lowest magnitude of 51.44 and 1.60 (Figure 5d). The ZNDX indicated 16 droughts with the highest and lowest of 21.66 and 0.05 (Figure 5e).

Cisco yielded the highest severity of 2.57 km^3/year during 2003-04 and lowest of 0.19 km^3/year during 1850-67. Green yielded the highest severity of 1.21 km^3/year during 1581-1608 and lowest of 0.01 km^3/year during 1939-43. Lee's Ferry indicated the highest and lowest severity of 4.37 km^3/year and 0.19 km^3/year during 1580-1605 and 1863-65 respectively. The PHDI indicated the highest severity of 1.84/year during 1580-1607 and lowest severity of 0.16/year during 1710-19. The ZNDX indicated the highest severity of 0.68/year during 1579-1605 and lowest severity of 0.03 during 1851-52.

The most severe droughts using this procedure did not occur in the past 100 years. The largest droughts in terms of magnitude occurred during the late 1500s (Cisco, Green, Lee's Ferry, and PHDI) and mid 1600s (Palmer Z). The analysis of Green and PHDI did not identify the current drought, but the Cisco, Lee's Ferry, and ZNDX positioned the current drought as the 6th to 13th worst in terms of magnitude and 1st to 3rd in terms of severity in the history of last 500 years (Table 3 and Table 4)

The 10-year moving average of the adjusted reconstructed streamflows; Cisco, Green, and Lee's Ferry were compared with the Stockton and Jacoby (1976) reconstruction (Figures 5a-c). The two reconstructions showed similar variability; however, the long-term means were different. The adjusted reconstructed drought variables of this study confirm that the late 1500s drought was the most severe drought in terms of magnitude for the past 500 years which is also consistent to the streamflow reconstructions by Hidalgo *et al.* (2000), Stockton and Jacoby (1976) and Stahle *et al.* (2000).

TABLE 5. Frequency of the Current Drought in the Upper Colorado River Basin Considering Multiple Drought Variables, Different Drought Identification Methods and Different Frequency Methods.

Variables	Drought Identification Method	Ranking Approach for Magnitude (CASE I)	Renewal Method (Magnitude & Duration) (CASE II)
Cisco	1	64	65
	5	43	44
	10	57	58
Green	1	47	58
	5	57	57
	10	No drought	No drought
Lee's Ferry	1	73	90
	5	73	74
	10	85	103
PHDI	1	47	47
	5	39	40
	10	No drought	No drought
ZNDX	1	47	47
	5	37	38
	10	39	47

Drought Frequency Results

The results of the two different approaches, ranking approach and renewal method of frequency analysis, are presented in Table 5. Both the methods yielded similar results ranging from low to high return periods for the current drought. Both approaches provided similar return periods of current drought ranging from 37 to 103 years depending upon the drought variables and method. This is reasonable considering that the frequency analysis was based on the historical plus adjusted reconstructed data of 500 years data.

CONCLUSIONS

This study summarizes 500 years of drought in the UCRB and places the current drought (2000-2004) as the worst in the historical record, but other larger droughts have occurred in the reconstructed record. The current drought, combined with increased water supply demand has exacerbated the impacts and has severely stressed the storage at the major reservoirs of the Colorado River – Lake Mead (Hoover Dam) and Lake Powell (Glen Canyon Dam).

The sensitivity of drought ranking and the frequency of the current drought were evaluated considering different procedures of multiple drought variables and different frequency methods for the past 500 years. The results were consistent in most cases for the most severe drought in the record and the ranking of the current drought. The procedure that uses the 10-year moving average for identifying drought periods (Drought Identification Method "10") considerably decreased the number of droughts, but did not change the magnitude significantly in the case of most of the severe droughts. Analysis indicated that the most severe drought in terms of magnitude occurred during the late 1500s for most of the cases of streamflow stations PHDI and ZNDX. It was also concluded that the current drought is the worst in the observed record (1923 to present) and this drought is the 7th to 14th worst in terms of magnitude and 1st to 12th worst in terms of severity in the past 500 years. Frequency analysis indicated that the current drought has a return period of 39-103 years depending on the methods used. If the current drought persists into the future, the current drought ranking and frequency may change depending upon the future magnitude of the drought variables.

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