Rio Grande and Rio Conchos water supply variability over the past 500 years

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ABSTRACT: The Rio Grande is a major source of water for parts of Mexico and the USA. The 2 main source regions for the Rio Grande system are the San Juan Mountains of the southern Rocky Mountains and the Sierra Madre Occidental in Mexico, which is the headwaters for the Rio Conchos, the largest tributary of the Rio Grande. Precipitation and streamflow from these 2 source regions are largely independent of each other; winter snowpack is the dominant contributor to the annual streamflow north of the USA–Mexico border, and the North American monsoon is a key factor in the Rio Conchos basin. Reconstructions of water year (October–September) streamflow for a gauge in the upper Rio Grande, 1508–2002, and of October–July precipitation in the Rio Conchos watershed region, 1649–1993, also indicate a lack of correlation between the 2 basins over century time scales. Despite this lack of correlation, periods of concurrent multiyear drought have occurred over the past 4 centuries, most notably in the 1770s, 1890s and 1950s. These rare concurrent droughts in the upper Rio Grande and Rio Conchos source regions may arise from large-scale forcing out of the Pacific Ocean and will be relevant to the binational planning of these water resources, which serve a large and growing population of users.

KEY WORDS: Rio Grande · Rio Conchos · Water resources · Dendrochronology · Paleoclimate

1. INTRODUCTION

The Rio Grande (Rio Bravo in Mexico) is one of 2 rivers shared by Mexico and the USA. It is a critical source of water for both countries, supplying water to 5 million people, 4 million of whom live along the USA–Mexico border. The Rio Grande is the fifth longest river in North America (2830 km) and has a drainage basin encompassing 870 000 km²; slightly more than half of this area contributes to flow (Dahm et al. 2005). The Rio Grande is considered one of the most impacted rivers in the world and has multiple issues that are related to water quality and quantity (Dahm et al. 2005).

The headwaters of the Rio Grande lie in the San Juan Mountains of Colorado and the runoff is largely from snowmelt. Peak flows for the portion of the river dominated by snowmelt occur from April to June. The average Rio Grande flow in northern New Mexico is about 43 m³ s⁻¹. Flows become very limited downstream from the border at El Paso, Texas, and Ciudad Juárez, Mexico. From here, the Rio Grande flow consists mostly of wastewater and irrigation return flows until its confluence with the Rio Conchos (Everitt 1993, Miyamoto et al. 1995, Schmandt et al. 2000). After this point, the main contribution to the Rio Grande comes from the Rio Conchos, which has its headwaters in the Sierra Madre Occidental, a mountain range in northeastern Mexico (Fig. 1). Above the confluence with the Rio Conchos, the Rio Grande average annual flow is about 3 m³ s⁻¹, while below this confluence the flow averages about 30 m³ s⁻¹ (Dahm et al. 2005).

Unlike the upper part of the Rio Grande, the Rio Conchos watershed is strongly under the influence of the North American monsoon. Over 50% of
the annual precipitation in this region is delivered through the monsoon between mid-June and mid-September (Dahm et al. 2005), although some summer precipitation is due to tropical storms in certain years. In winter, westerly storms bring additional precipitation, but cool season (November–May) flows make up just 10% of the total annual flow. Research in the adjacent Rio Yaqui basin indicates that although cool season precipitation represents a smaller proportion of the annual precipitation, it is highly correlated with winter streamflows, which, in turn, are highly correlated with annual reservoir inflows (Nicholas & Battisti 2008), and this is probably the case in the Rio Conchos as well. Winter flows are important for replenishment of reservoirs and have greater efficiency than summer runoff because of lower evaporation rates during the cool season. The Rio Conchos drainage area accounts for about 14% of the total drainage area of the Rio Grande, but its flow accounts for a much greater proportion of the total flow because of upstream depletions in the Rio Grande. The Rio Conchos is the source for much of the flow through Big Bend National Park, Texas, and its flows are a primary source of water for the Amistad International Reservoir, the main reservoir in the lower Rio Grande basin (IBWC 2009) (Fig. 1).

The Rio Grande is a critical water supply for the region through which it passes. Irrigated agriculture production below New Mexico’s Elephant Butte Reservoir, the largest reservoir on the upper Rio Grande (Fig. 1), accounts for 80% of the water withdrawals and is a large contributor to local economies (e.g. over US$7 billion to the county of El Paso, Texas, in 2003; Michaelson 2004). The river also provides water for the Middle Rio Grande Conservancy District, 6 northern New Mexico pueblos and in-stream flows for the endangered Rio Grande silvery minnow Hybognathus amarus (US Bureau of Reclamation 2003).

The region known as Paso del Norte, from Elephant Butte Reservoir to Presidio/Ojinaga, is experiencing population growth, resulting in expanded water demands for municipal and industrial uses in cities that include Las Cruces and El Paso in the USA and Ciudad Juárez and Chihuahua in Mexico. Populations for this region are projected to exceed 4 million by 2020, from just over 2 million in 2000 (PDNWTF 2001). Municipal and industrial water use is projected to increase by 76% between 2000 and 2020 (PDNWTF 2001). Below Presidio/Ojinaga, the Rio Conchos and its tributaries support agricultural production, with 93% of the flow being used for irrigated agriculture (Dahm et al. 2005).

2. ADMINISTRATION AND MANAGEMENT

The Rio Grande is a complex river system distinguished by a legacy of international treaties and multiple administrative agencies. Three main treaties allocate Rio Grande water resources: 2 international treaties, in 1906 and 1944, and 1 interstate treaty, in 1938. The 1906 international treaty between the USA and Mexico allocated 78 million m³ of Rio Grande flow annually to Mexico at Ciudad Juarez (Thomas et al. 1963). The Rio Grande Interstate Compact was negotiated in 1938 between Colorado,
New Mexico and Texas. It allocated upper Rio Grande flow, as measured near the Colorado–New Mexico state line, for deliveries to New Mexico and at Otowi Bridge in New Mexico for deliveries to Elephant Butte Reservoir for allocation to Texas (Thomas et al. 1963) (Fig. 1). The 1944 international treaty addressed Rio Grande flow in the lower basin between Fort Quitman, Texas, and the Gulf of Mexico. In this treaty, Mexico’s allotment includes two-thirds of the flow from the Rio Conchos and 5 smaller Mexican tributaries (Rios San Diego, San Rodrigo, Escondido, Salado, Arroyo de las Vacas), all the water from the San Juan and Alamo rivers and 50% of the flows from unmeasured tributaries. The USA is to receive one-third of the flow from the Rio Conchos and the 5 Mexican tributaries, all the flows from US tributaries (Pecos and Devils rivers, Goodenough Spring and Alamito, Terlingua, San Felipe and Pinto creeks) and 50% of unmeasured tributaries. The US allocation is no less than an annual average of 431.7 million m³ in 5 yr cycles (i.e. over a 5 yr period) from the Rio Conchos and the other Mexican tributaries (Spener 2007).

Drought and growing water demands have resulted in water conflicts in recent years (Kelly 2002). Historically, unregulated runoff was sufficient to fulfill Mexico’s treaty obligations to the USA (Spener 2007). But droughts, coupled with increased irrigation in Mexico, led to delivery deficits in the mid to late 1990s and early 2000s. While Mexico claimed extraordinary drought as the reason for the deficits, extraordinary drought is not defined in the 1944 treaty, and conflict persisted until the obligation was paid off in 2005 when reservoirs refilled due to high precipitation (Dahm et al. 2005). The conflict brought to the forefront the issue of drought extremes and whether allowances due to drought should be made for Mexico’s delivery obligations.

In some respects, the portion of the Rio Grande that is supplied by the San Juan Mountain headwaters and the Rio Conchos may be considered to be 2 different rivers. The source regions, climatic controls and administration for each, while not mutually exclusive, are largely distinct, and the upper and lower parts of the river are legally managed as 2 different systems (A. Michaelsen pers. comm.). However, management must consider the entire river, and the relationship between these 2 parts is key to the administration of the river in a way that meets the needs of all users.

In this study, we examined the 2 source regions of the Rio Grande system, the Rio Grande and Rio Conchos headwaters, to determine the range of hydro-climatic variability that has occurred, and the nature and degree of coherence of drought in these 2 areas over the past 4 centuries. To gain this long-term perspective, we generated and compared tree-ring based reconstructions of water year (October–September) streamflow for the Rio Grande headwaters and October–July total precipitation in the Rio Conchos watershed. Although Rio Conchos precipitation for October–July does not reflect a large part of the monsoon precipitation or the occasional early fall tropical storm, constraints of the tree-ring data currently available prevent high quality reconstructions of total monsoon precipitation in this region. However, the October–July total correlates well with water year precipitation and may be considered a proxy for water year precipitation. Thus, it can provide some insights into the relationship between the hydroclimatology of the 2 regions. Although tree-ring based reconstructions of the summer Palmer Drought Severity Index (PDSI) exist for both regions (Cook et al. 2007), here we were interested in the temporal and spatial variability of water supply, rather than drought per se, although we did consider the spatial pattern of drought from PSDI as part of the analysis.

3. INSTRUMENTAL DATA

The common time period for the instrumental records for the Rio Grande and Rio Conchos watersheds spanned the years 1922–2006. We used the gauge at Del Norte, Colorado, to represent headwaters flow because of the long and relatively depleted flow record available (i.e. few or no diversions of flow have been made for irrigation or other uses upstream from this gauge). Annual flows, measured as the water year from October to September, were obtained from the Rio Grande (Colorado) Water Conservation District. The Rio Conchos lacks long, natural flow records. Although less than ideal for comparison with the Rio Grande flow, monthly divisional precipitation data were used, obtained from A. V. Douglas (pers. comm.). We used Mexican Climate Division 5 because it closely coincides with the upper Rio Conchos watershed (Fig. 1). Water year precipitation was used for the comparison with Rio Grande water year streamflow. Mexican Division 5 October–July precipitation was also analyzed, as this was the period used in the Rio Conchos reconstruction. October–July total precipitation represented 58% of the annual precipitation and was correlated with water year precipitation (r = 0.865, p < 0.01).
Water year precipitation in the Rio Conchos watershed and water year streamflow in the Rio Grande headwaters were not significantly correlated ($r = 0.080$, $p = 0.496$; Rio Conchos October–July precipitation and water year Rio Grande streamflow were also not significantly correlated $r = 0.111$, $p = 0.313$). For comparison, upper Rio Grande basin water year precipitation (gridded data from parameter–elevation regressions on independent slopes model [PRISM]; Daly et al. 2002) was significantly, although not highly correlated with Rio Conchos water year precipitation ($r = 0.305$, $p = 0.005$, $n = 85$) as well as with Rio Conchos October–July precipitation ($r = 0.298$, $p = 0.006$, $n = 85$). A period of below average flows in the Rio Grande in the 1960s was one of above average precipitation in the Rio Conchos, and 1981, which was one of the driest winters throughout Colorado, was one of the 5 wettest years in the Rio Conchos. Conversely, the 1920s were mostly dry in the Rio Conchos, while this was a period of wet conditions in the Rio Grande headwaters (Fig. 2). Some droughts were shared and drought years during the 1950s (1951, 1953 and 1956) fell into the driest 25th percentile of both records, as did the individual drought years of 1934 and 1974 (for the October–July total as well).

The 2 time series, for Rio Grande streamflow and Rio Conchos precipitation, graphed as 5 yr moving averages showed some periods of coherence, most notably in the 1930s and 1950s, which were periods of widespread drought across large areas of North America. Although the 1930s drought was not as severe in the southwestern USA compared with that in the Great Plains (Fye et al. 2003), it does appear to have been a more persistent period of below average precipitation in the Rio Conchos basin (Fig. 2). The heart of the 1950s drought was in the southwestern USA and northern Mexico (Fye et al. 2003, Stahle et al. 2009), and its severity is evident in both records. The drought of record (in terms of cumulative deficits over runs of below average years) in the Rio Grande headwaters was the most recent drought, which appeared to be less severe in the Rio Conchos water year precipitation, and in the October–July precipitation did not appear as a period of drought at all (Fig. 2, lower panel), although it was a period of anomalously warm temperatures (Stahle et al. 2009).

In summary, the instrumental records suggest that although the hydroclimatic variability in the 2 watersheds is not closely coupled, there were some periods (the 1950s in particular) when drought occurred in both watersheds, which could be due to chance and/or to a large-scale circulation feature.

4. HYDROCLIMATIC RECONSTRUCTIONS

4.1. Rio Grande headwaters

Moisture-sensitive tree-ring species (*Pinus ponderosa*, *Pinus edulis* and *Pseudotsuga menzeisii*) in Colorado and other parts of the western USA are well correlated with streamflow because both annual tree growth and water year flows reflect the cumulative effects of precipitation (particularly snowfall) and evapotranspiration over the course of the water year (Meko et al. 1995, Woodhouse et al. 2006). A number of tree-ring chronologies from these species are available for the upper Rio Grande watershed and neighboring watersheds with similar climate (i.e. the southern portion of the Colorado River basin and the Arkansas River basin) (International Tree-Ring Data Bank; Woodhouse et al. 2006). For the reconstruction
of the Rio Grande near Del Norte, these chronologies were screened by using a 2-step process: (1) chronologies were screened to include the common time period, 1508–2002; (2) these chronologies were further screened, retaining those that were significantly correlated (p < 0.01) with the Rio Grande gauge record, for the period common to both tree-ring chronologies and gauge data, 1890–2002, and for this period split into halves. A total of 15 chronologies passed both levels of screening and were candidate predictors for the reconstruction model. Residual chronologies (with persistence considered to be biological in origin removed; Fritts 1976) were used because the gauge record contained no significant low-order autocorrelation.

To develop a reconstruction model, the tree-ring chronologies were calibrated with the gauge record over the full common period (1890–2002) by means of a forward stepwise regression. A model resulted in which 4 predictors explained 71% of the total variance (Tables 1 & 2A, Fig. 3a). This model met regression assumptions, including a lack of significant autocorrelation (as indicated by the Durbin-Watson D and Lag 1 autocorrelation; Table 2B), although residuals had a slight nonsignificant negative trend. A leave-one-out cross validation process (Michaelsen 1987) confirmed the skill of the reconstruction model (Table 3). Validation statistics, the reduction of error (RE) (Fritts et al. 1990) and root mean square error (RMSE) (Weisberg 1985), were generated to assess the skill of the model with estimates from the leave-one-out process (Table 3). The RE tests the skill of the model compared with estimates based on the mean of the validation data. The RMSE for the validation data is comparable with the standard error (SE) of the estimate for the calibration data. Both are used to assess possible model overfit. For further validation of the skill of this set of predictor chronologies, separate stepwise regression models were run on the early and late halves of the common time period, resulting in almost identical sets of predictors being selected, and on models that validated well on the withheld parts of the data (Table 3). The full Rio Grande flow reconstruction generated from this model covers the years from 1508 to 2002.

The Rio Grande reconstruction indicates periods of more severe and persistent low flow than any recorded in the gauge record. One of longest runs of

Table 1. Chronologies used in reconstruction models. All chronologies are available through the International Tree-Ring Data Bank (www.ncdc.noaa.gov/paleo/treering.html). pied: Pinus edulis; psme: Pseudotsuga menzeisii

<table>
<thead>
<tr>
<th>Name</th>
<th>Code</th>
<th>Species</th>
<th>Years</th>
<th>Location</th>
<th>Source</th>
</tr>
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<tr>
<td>Rio Grande</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slickrock</td>
<td>SLK</td>
<td>pied</td>
<td>1490–2002</td>
<td>Colorado</td>
<td>Woodhouse et al. 2006</td>
</tr>
<tr>
<td>Trail Gulch</td>
<td>TRG</td>
<td>pied</td>
<td>1402–2002</td>
<td>Colorado</td>
<td>Woodhouse et al. 2006</td>
</tr>
<tr>
<td>Natural Arch</td>
<td>ARC</td>
<td>pied</td>
<td>1508–2002</td>
<td>Colorado</td>
<td>Present study</td>
</tr>
<tr>
<td>Cathedral Creek</td>
<td>CAT</td>
<td>psme</td>
<td>1366–2002</td>
<td>Colorado</td>
<td>Woodhouse et al. 2006</td>
</tr>
<tr>
<td>Rio Conchos</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earlywood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cerro Baraja</td>
<td>CBA</td>
<td>psme</td>
<td>1439–2006</td>
<td>Durango</td>
<td>Stable et al. 2000b</td>
</tr>
<tr>
<td>Creel</td>
<td>CIA</td>
<td>psme</td>
<td>1645–1993</td>
<td>Chihuahua</td>
<td>Stable et al. 2000b</td>
</tr>
<tr>
<td>Latewood</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El Tabacote</td>
<td>TAB</td>
<td>psme</td>
<td>1622–1993</td>
<td>Chihuahua</td>
<td>Stable et al. 2000b</td>
</tr>
<tr>
<td>Creel</td>
<td>CIA</td>
<td>psme</td>
<td>1649–1993</td>
<td>Chihuahua</td>
<td>Stable et al. 2000b</td>
</tr>
<tr>
<td>Las Tinejas</td>
<td>TIN</td>
<td>psme</td>
<td>1624–1993</td>
<td>Chihuahua</td>
<td>Stable et al. 2000b</td>
</tr>
<tr>
<td>Cerro Baraja</td>
<td>CBA</td>
<td>psme</td>
<td>1440–2006</td>
<td>Durango</td>
<td>Stable et al. 2000b</td>
</tr>
</tbody>
</table>

Table 2. Regression statistics. (A) Statistics for the 2 reconstruction models. (B) Regression model results. Rio Grande reconstruction model based on 1890–2002; Rio Conchos reconstruction model based on 1940–1977

A Regression terms

<table>
<thead>
<tr>
<th>Regression terms</th>
<th>b coefficient</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rio Grande</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>−3081.5</td>
<td>−0.073</td>
<td>0.942</td>
</tr>
<tr>
<td>Slickrock</td>
<td>230233</td>
<td>5.432</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Trail Gulch</td>
<td>191766</td>
<td>5.096</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Natural Arch</td>
<td>151537</td>
<td>3.512</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cathedral Creek</td>
<td>790661.1</td>
<td>2.224</td>
<td>0.028</td>
</tr>
<tr>
<td>Rio Conchos</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>69.4</td>
<td>1.498</td>
<td>0.144</td>
</tr>
<tr>
<td>Earlywood average</td>
<td>229.9</td>
<td>4.971</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Latewood average</td>
<td>202</td>
<td>2.807</td>
<td>0.008</td>
</tr>
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</table>

B Regression model results

<table>
<thead>
<tr>
<th>Regression model results</th>
<th>No. of cases</th>
<th>R²</th>
<th>F</th>
<th>p</th>
<th>Durban-Watson D</th>
<th>Lag 1 autocorrelation (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rio Grande</td>
<td>113</td>
<td>0.713</td>
<td>67.242</td>
<td>&lt;0.001</td>
<td>1.727α</td>
<td>0.131β</td>
</tr>
<tr>
<td>Rio Conchos</td>
<td>35</td>
<td>0.532</td>
<td>18.210</td>
<td>&lt;0.001</td>
<td>1.900α</td>
<td>0.037β</td>
</tr>
</tbody>
</table>

αNull hypothesis of zero first order autocorrelation cannot be rejected at the 0.01 α-level
βNot significantly different (p > 0.05) from zero, based on Ljung–Box Q test
below average flows was 7 yr in 1579–1585. This period coincides with drought conditions that have been documented throughout western North America (e.g. Stahle et al. 2000a). However, the most persistent drought in this record occurred 1873–1883 (Fig. 4a). Flows over this 11 yr period averaged 74% of the long-term average. The most severe drought (in terms of annual deficit) was a 5 yr run, 1622–1626, during which flows averaged 63% of the long-term average. This period followed one of the longest runs of above average flows, second only to the wet period of the early 20th century (Fye et al. 2003, Woodhouse et al. 2005) (Fig. 4a).

4.2.  Rio Conchos basin precipitation

The relationships between tree growth and precipitation in the Rio Conchos basin are less straightforward than those in the Rio Grande headwaters because of the monsoon precipitation season. Although annual tree-ring widths tend to correspond to cool season precipitation, measurements of subannual increments of the ring, formed during early and late parts of the growing season (called the earlywood and latewood, respectively), can provide information about both cool season and summer moisture. A number of chronologies for Mexico have been gener-
Table 3. Rio Grande streamflow reconstruction model calibration and verification statistics. \( r(c) \) and \( r(v) \) are the correlations between observed and estimated values for calibration and verification periods, respectively. RE: reduction error; RMSEv: root mean square error for verification period. Site codes for predictors: see Table 1

<table>
<thead>
<tr>
<th>Model</th>
<th>Predictors</th>
<th>( r(c) )</th>
<th>( R^2 ) (( R^2 ) adjusted)</th>
<th>SE estimate</th>
<th>( r(v) )</th>
<th>RE</th>
<th>RMSEv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>SLK,TRG,ARC,CAT</td>
<td>0.845</td>
<td>0.713 (0.703)</td>
<td>121640</td>
<td>0.69</td>
<td>123784</td>
<td></td>
</tr>
<tr>
<td>1st half cal</td>
<td>SLK,TRG,ARC</td>
<td>0.84</td>
<td>0.705 (0.688)</td>
<td>121700</td>
<td>0.834</td>
<td>0.682</td>
<td>133811</td>
</tr>
<tr>
<td>2nd half cal</td>
<td>SLK,CAT,TRG,ARC</td>
<td>0.863</td>
<td>0.745 (0.735)</td>
<td>115807</td>
<td>0.823</td>
<td>0.653</td>
<td>137918</td>
</tr>
</tbody>
</table>

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ated that include measurements of earlywood, latewood and full ring-width growth increments. For the Rio Conchos watershed reconstruction, a set of primarily Mexican tree-ring chronologies from moisture sensitive species (Stahle et al. 2000b, Cleaveland et al. 2003, Villanueva-Díaz et al. 2008, 2009) was screened in a 2-step process: (1) identification of tree-ring chronologies with the common years from 1772 to 1993; (2) selection of chronologies that were located in climate divisions with precipitation that was significantly correlated with Division 5 precipitation for one or more months, including parts of northern and eastern Mexico and Texas (Mexican data from A. V. Douglas pers. comm.; Texas data from the NOAA National Climatic Data Center). This initial screening process resulted in a set of chronologies from 13 sites, 11 of which included both earlywood, latewood and full ring chronologies, from *Pinus ponderosa*, *Pseudotsuga menzeesi* and *Taxodium mucronatum*. Further screening identified significant correlations with Division 5 precipitation for the months from October before the growth year to September of the growth year. Full ring and earlywood chronologies correlated with October–May precipitation, while a handful of latewood chronologies correlated with June and July precipitation. We elected to use the earlywood and latewood chronologies because of their complementary seasonal climate signals and the residual form of the chronologies, as we did with the Rio Grande reconstruction. Individual latewood chronologies were regressed on associated earlywood chronologies to remove the dependence of the latewood growth on the earlywood growth (Meko & Baisan 2001), and the resulting adjusted latewood residual chronologies were used for subsequent analysis.

Based on correlation results that tested different combinations of total monthly precipitation, a set of 2 potential predictors was generated by averaging the 2 earlywood chronologies and the 4 latewood chronologies that were most strongly correlated with the first half of the precipitation time series was dissimilar to the second half with respect to the mean and variance, and it was not possible to calibrate a model on one-half of the data that would perform well on the other half. In addition, the number of climate station records available varies widely through time, with fewer stations at the beginning of the period and a marked loss of stations over the last 3 decades (Zhu & Lettenmaier 2007), so this middle period is likely to be the best reflection of regional climate. The 2 predictors, the averages of earlywood and latewood chronologies, were used in a stepwise regression to estimate October–July total precipitation for 1940–1974. Both predictors entered, resulting in a regression model that explained 53% of the total variance and met regression assumptions, although residuals displayed a slight nonsignificant positive trend (Table 2A,B). This model was validated on the data withheld from the calibration, and results indicate modest skill of the reconstruction model on the independent data (Table 4, Fig. 3b). The correlation between observed and estimated values for the full common period, 1922–1993, was \( r = 0.653 \) (\( p < 0.05 \)). A full reconstruction was then generated for the years 1649–1993.

The Rio Conchos precipitation reconstruction was characterized by runs of below average precipitation years (based on the long-term average, 1649–1993) that included periods that lasted 5, 6, 7 and 8 yr. Two of these periods overlapped or fell within periods of persistent drought in the Rio Grande headwaters record. The 7 yr period 1729–1735 overlapped with a 6 yr stretch of low flows in the Rio Grande, but annual precipitation averaged 91% of the mean, so although persistent, deficits for this period were not extreme. The 5 yr period in the Rio Conchos reconstruction, 1876–1880, fell within the most persistent low flow episode in the Rio Grande reconstruction, although deficits for this set of years were also not as severe in the Rio Conchos precipitation reconstruction (Fig. 4b). The drought with the most extreme
deficits was the period 1890–1894, during which precipitation averaged 70% of the mean. However, unlike the Rio Grande reconstruction, the run of greatest duration occurred in the 20th century, from 1950 to 1957 (Fig. 4b), in which an average annual precipitation of 82% of the long-term mean occurred. This period of drought was the most severe drought in Mexico since the drought of the 1560s (Stahle et al. 2009). After a single year of above average precipitation in 1958, this 8-yr period was followed by another prolonged period of below average precipitation, from 1961 to 1963, although this period of drought was much less severe.

4.3. Comparison of Rio Grande reconstructions

As in the instrumental records, the reconstructions of Rio Grande headwaters flow and Rio Conchos October–July precipitation were not significantly correlated over the instrumental period (1922−1993: \( r = 0.101, p = 0.400 \)), but they were significantly although weakly correlated over the full reconstruction period (1649−1993: \( r = 0.163, p = 0.002 \)). Also in common with the instrumental records, most of the severe drought years were different between the 2 reconstructed records, but a handful of the very driest (10th percentile) are shared, most of which occurred in the 18th century (1748, 1763, 1773, 1798). The single year 1934 was the only year in the 20th century that was in the driest 10th percentile in both records. When smoothed, periods of shared drought became more obvious (Fig. 5). In particular, the periods centered on the 1950s, the late 19th century and 1775 stand out as periods of coherent drought in the 2 regions. Of these periods, the 1950s was the most severe drought period in the Rio Conchos in the past 3½ centuries, and the peak of this drought occurred simultaneously in both basins. The severity of this drought in the southwestern USA, the southern Great Plains and northern Mexico has been well documented (e.g. Fye et al. 2003, Stahle et al. 2009). The late 19th century contained several periods of sustained drought in the Rio Grande headwaters, including the most sustained period of drought in 500 yr, but drought phasing in the 2 basins was not synchronous. This period has been documented in other reconstructions for northern Mexico (Cleaveland et al. 2003), Durango, Mexico (Villanueva-Díaz et al. 2007) and the Nazas basin (Villanueva-Díaz et al. 2005), as well as in regions of the USA, notably the southern Great Plains (Stahle & Cleaveland 1988, Herweijer et al. 2006). The period of drought centered on 1775 is in phase in both basins, but is less severe in the Rio Conchos, although there is some historical documentation for severe drought during the 1770s in Chihuahua (Endfield & Fernandez Tejedo 2006).

Spatial patterns for the 3 periods of coinciding drought were assessed by using gridded tree-ring reconstructions of summer PDSI (Cook et al. 2007). Composite maps show the spatial coverage for the most severe droughts in these 2 basins: 1772−1776, 1892−1894 and 1953−1956 (Fig. 6). An additional period of concurrent drought in the late 1660s (1666−1668) is also shown, which indicated widespread, severe drought conditions, although it was less severe than the 1950s drought.

Table 4. Mexico Climate Division 5 (Rio Conchos watershed) October–July total precipitation reconstruction model calibration and verification statistics. \( r(c) \) and \( r(v) \) are the correlations between observed and estimated values for calibration and verification periods, respectively. RE: reduction error; RMSEv: root mean square error for verification period

<table>
<thead>
<tr>
<th>Period</th>
<th>( r(c) )</th>
<th>( R^2 ) (( R^2 ) adjusted)</th>
<th>SE estimate</th>
<th>( r(v) )</th>
<th>RE</th>
<th>RMSEv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration</td>
<td>1940−1974</td>
<td>0.73</td>
<td>0.533 (0.504)</td>
<td>59</td>
<td>0.593</td>
<td>0.315</td>
</tr>
<tr>
<td>Verification</td>
<td>1922−1939, 1975−1993</td>
<td>0.593</td>
<td>0.315</td>
<td>79.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Reconstructed streamflow for Rio Grande water year flow and Rio Conchos watershed October–July total precipitation, 1649−1993, as percent of average, smoothed with a 20 yr spline. Shading indicates periods when values in both reconstructions are below average.
5. DISCUSSION AND CONCLUSIONS

The hydroclimatic variability in the headwaters of the Rio Grande and its principal tributary, the Rio Conchos, is not strongly coupled, particularly on a year-to-year basis. This is true for the period of instrumental records, and also appears to be true for the extended reconstruction period, 1649–1993. Reconstructions of Rio Grande streamflow and Rio Conchos watershed precipitation show a great deal of variability over past centuries, and include periods of persistent drought that range from 5 to 8 yr. The high degree of temporal variability ensures that droughts occur concurrently in both basins at irregular intervals. Are there common climatic drivers that lead to severe drought in both basins, or do concurrent droughts occur by chance?

A consideration in addressing this question is the seasonality of precipitation, its contribution to streamflow and the moisture delivery mechanisms in both basins. Although the upper Rio Grande basin has a summer precipitation maximum, winter snowpack is the main contribution to annual flows. Winter precipitation is delivered through westerly flow and storms guided by the jet stream. The Rio Conchos watershed is dominated by summer monsoon precipitation and by tropical storms in some years, but cool season precipitation (October–May) makes up about 28% of the annual total. The Rio Conchos reconstruction presented here, for October–July precipitation, is an expression of both cool season precipitation, a result of the extreme southernmost influence of the jet stream, and the first part of the monsoon season. Thus, the common feature of both basins is the precipitation resulting from the cool season storm track. One control on the position of the storm track that can...
influence both regions is the El Niño/Southern Oscillation (ENSO). The relationship between ENSO events and cool season precipitation in northern Mexico and the southern and southwestern USA has been documented (Ropelewski & Halpert 1986, 1989, Kiladis & Diaz 1989); an El Niño event results in a southerly storm track, while during a La Niña event, the storm track moves to the north, leaving the southwestern USA and Mexico dry (e.g. Compo & Sardeeshmukh 2004, Seager et al. 2009). Although the statistical relationship between ENSO events and USA and Mexico dry (e.g. Compo & Sardeeshmukh 2004, Seager et al. 2009). Although the statistical relationship between ENSO and Rio Grande headwaters flow is not significant $r = -0.149$, $p = 0.187$; winter Southern Oscillation Index, 1922–2001, NOAA Climate Prediction Center), low flow years do correspond to some La Niña events (e.g. 1951, 1956, 1974 and 2000, based on an index of sea surface temperature [SST] anomalies in the El Niño 3.4 region, NOAA Climate Prediction Center), which suggests there is a nonlinear relationship in this basin. The correlation between ENSO and cool season (October–May) precipitation for the Rio Conchos watershed is significant $r = -0.437$, $p < 0.001$, $n = 80$; thus ENSO may at times be a common control on winter precipitation in both regions. Both the 1950s and 1890s droughts occurred during La Niña events (Seager et al. 2009).

However, for severe concurrent droughts in both basins, it is necessary to have both a dry winter, typically a La Niña event, and a weak monsoon. In the North American monsoon region, La Niña and El Niño events tend to correspond with greater and lesser monsoon precipitation, respectively (Higgins et al. 1998, 1999, Castro et al. 2001). This suggests that a dry summer and a dry winter will not occur during the same phase of ENSO, although if a La Niña event changes sign in the late spring to El Niño conditions by summer, then a dry winter could well be followed by a dry summer. The decade of the 1950s contained a number of years with below average observed and reconstructed streamflow or precipitation in both basins (6 of 10 yr, 1950–1951 and 1953–1956). This decade was characterized by several strong La Niña events that generally coincided with drought that persisted into the warm season. The 1950s also coincided with the negative phase of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997), which can enhance La Niña effects (Gershunov & Barnett 1998) and may also influence monsoon variability (Higgins & Shi 2000, Castro et al. 2001). But the linkage between La Niña conditions and strong monsoons was not evident in the 1950s, and the role that the PDO may have played in the persistence of drought and monsoon precipitation is not clear. Further complicating this interpretation is the fact that October–July precipitation reflects both cool and warm season precipitation influences, but not the full monsoon season. In the 1950s drought years, the proportion of the October–July precipitation accounted for by June and July is just over one-half, which is consistent with the average June–July proportion over the full precipitation record and suggests that June and July were not unusual with respect to their contribution. Since both winter and summer were dry in northern Mexico over much of this period (Stahle et al. 2009), it is likely that other factors in addition to ENSO and Pacific decadal variability, such as Atlantic Ocean conditions, were responsible.

The reconstructed time series show periods when Rio Grande water year streamflow and Rio Conchos October–July precipitation were both in phase and out of phase (Fig. 5), indicating that one or more underlying circulation mechanisms influence both regions. Nicholas & Battisti (2008) found that cool season precipitation in the Rio Yaqui basin, adjoining the Rio Conchos basin, was strongly influenced by ENSO and highly correlated to annual reservoir inflow, which is in agreement with our results for the Rio Conchos. ENSO is also likely to be an important control on severe drought in the Rio Grande headwaters in at least some years. However, although there is a growing body of research examining the effects of ocean and atmosphere circulation on regional drought at annual and multidecadal timescales (e.g. Gershunov & Barnett 1998, Castro et al. 2001, Brown & Comrie 2004, Kiem & Franks 2004, McCabe et al. 2004, Verdon-Kidd & Kiem 2010), more research is needed on the relationship between cool and monsoon season precipitation and the circulation mechanisms that control their variability.

Concurrent drought in the Rio Grande headwaters and the Rio Conchos watershed, a component of natural hydroclimatic variability, must be considered in water resource management, along with a future that includes increasing water demands as well as climate changes that will further stress water supply and increase demand (Seager et al. 2007, Solomon et al. 2007). An acknowledgement that concurrent droughts have occurred in the past, and may occur in the future, will be relevant to the binational water policy discussions that address drought impacts in both basins. Long paleoclimatic records are critical for placing relatively uncommon events, such as concurrent drought across the full Rio Grande basin, in a long-term context and are useful for water resources management in other arid and semi-arid parts of the world (Kiem & Franks 2004, Verdon-Kidd & Kiem 2010).
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