

A Paleo Perspective of Alabama and Florida (USA) Interstate Streamflow

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Abstract: Seasonal reconstructions of streamflow are valuable because they provide water planners, policy makers, and stakeholders with information on the range and variability of water resources before the observational period. In this study, we used streamflow data from five gages near the Alabama-Florida border and centuries-long tree-ring chronologies to create and analyze seasonal flow reconstructions. Prescreening methods included correlation and temporal stability analysis of predictors to ensure practical and reliable reconstructions. Seasonal correlation analysis revealed that several regional tree-ring chronologies were significantly correlated ($p \leq 0.05$) with March–October streamflow, and stepwise linear regression was used to create the reconstructions. Reconstructions spanned 1203–1985, 1652–1983, 1725–1993, 1867–2011, and 1238–1985 for the Choctawhatchee, Conecuh, Escambia, Perdido, and Pascagoula Rivers, respectively, all of which were statistically skillful ($R^2 \geq 0.50$). The reconstructions were statistically validated using the following parameters: R^2 predicted validation, the sign test, the variance inflation factor (VIF), and the Durbin–Watson (D–W) statistic. The long-term streamflow variability was analyzed for the Choctawhatchee, Conecuh, Escambia, and Perdido Rivers, and the recent (2000s) drought was identified as being the most severe in the instrumental record. The 2000s drought was also identified as being one of the most severe droughts throughout the entire reconstructed paleo-record developed for all five rivers. This information is vital for the consideration of present and future conditions within the system.

Keywords: drought; streamflow; hydroclimate; dendrochronology; paleoclimatology; water resources

1. Introduction

Tree-ring based reconstructions of streamflow are advantageous to water planners and policy makers because they extend gage records beyond the observational period, which in turn provides a better understanding of the full range of natural flow variability and the associated climatic drivers within the hydrological system. However, to develop a reliable model of past streamflow conditions, the accuracy and length of the streamflow gage records are crucial for both validating and bias correcting the reconstructed values to that of the observed period. Although the United States Geological Survey (USGS) streamflow-gaging program began collecting streamflow data as early as 1887 CE, many gages lack continuous records [1–3]. Most streamflow gage data for rivers unimpacted by human activity consist of 60 years of data or fewer, which fails to capture the full range of

climate variability, therefore limiting the reliability of the overall modeled streamflow. Tree-ring chronologies (TRCs) often date back centuries and are used as a surrogate for hydroclimate data reconstruction to provide further historical insight [4–9], as certain tree species are sensitive to the moisture signal of the region and serve as robust proxies for streamflow reconstruction [2,8–15].

While dendrochronological reconstructions of hydroclimate, including streamflow, have been widely utilized in the western United States (US) due to the arid, moisture-limited environment [6,7,16–28], until recently, similar studies have been relatively limited in the southeastern US [3,8,14,29–34]. However, Crockett et al. [2] established TRCs to be useful and statistically significant proxies even in the humid subtropical climate of northern Florida. For another example, Harley et al. [14] demonstrated a strong reconstruction of streamflow in the Suwannee River over the period of 1550–2005 CE. Furthermore, multiple studies have utilized streamflow variability in the Southeast to identify hydroclimatic extremes (i.e., floods and droughts) and the associated climatic drivers (e.g., Atlantic Multi-decadal Oscillation (AMO), El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO)) of such events [1,35–43].

Water management has reached a critical point in the State of Florida. Recent estimates place Florida as the third most populous state in the US, and current water supply is insufficient to support the growing population of nearly 22 M residents, not to mention the millions of visitors each year [44]. Additionally, there has been an ongoing legal conflict regarding water supplies between the states of Alabama, Florida, and Georgia (the Tri-State Water Wars) since the 1980s CE [45]. With the compounding impacts of climate change and rising temperatures on drought frequency [46], interstate water policy conflict, and agricultural growth influencing fresh water supply, paleo-perspectives of the range and variability of Florida's rivers are critical to develop best management practices that meet the growing demands of water resources.

The objective of this study is to reconstruct streamflow at five different streamflow gages near the Alabama-Florida state border and to evaluate the severity of a recent decadal drought from a centennial-scale perspective. Tree-ring chronologies from the surrounding region were used to reconstruct streamflow for the following rivers: the Choc-tawhatchee River near Newton, AL, the Choctawhatchee River near Bruce, FL, the Conecuh River, the Escambia River, the Perdido River and the Pascagoula River (Figure 1). These intrastate hydrological reconstructions across multiple interstate borders of the northern Gulf of Mexico coast provide valuable information regarding the water availability and urban population growth in these areas, while also highlighting the need for additional TRCs and intrastate streamflow reconstructions throughout the region.

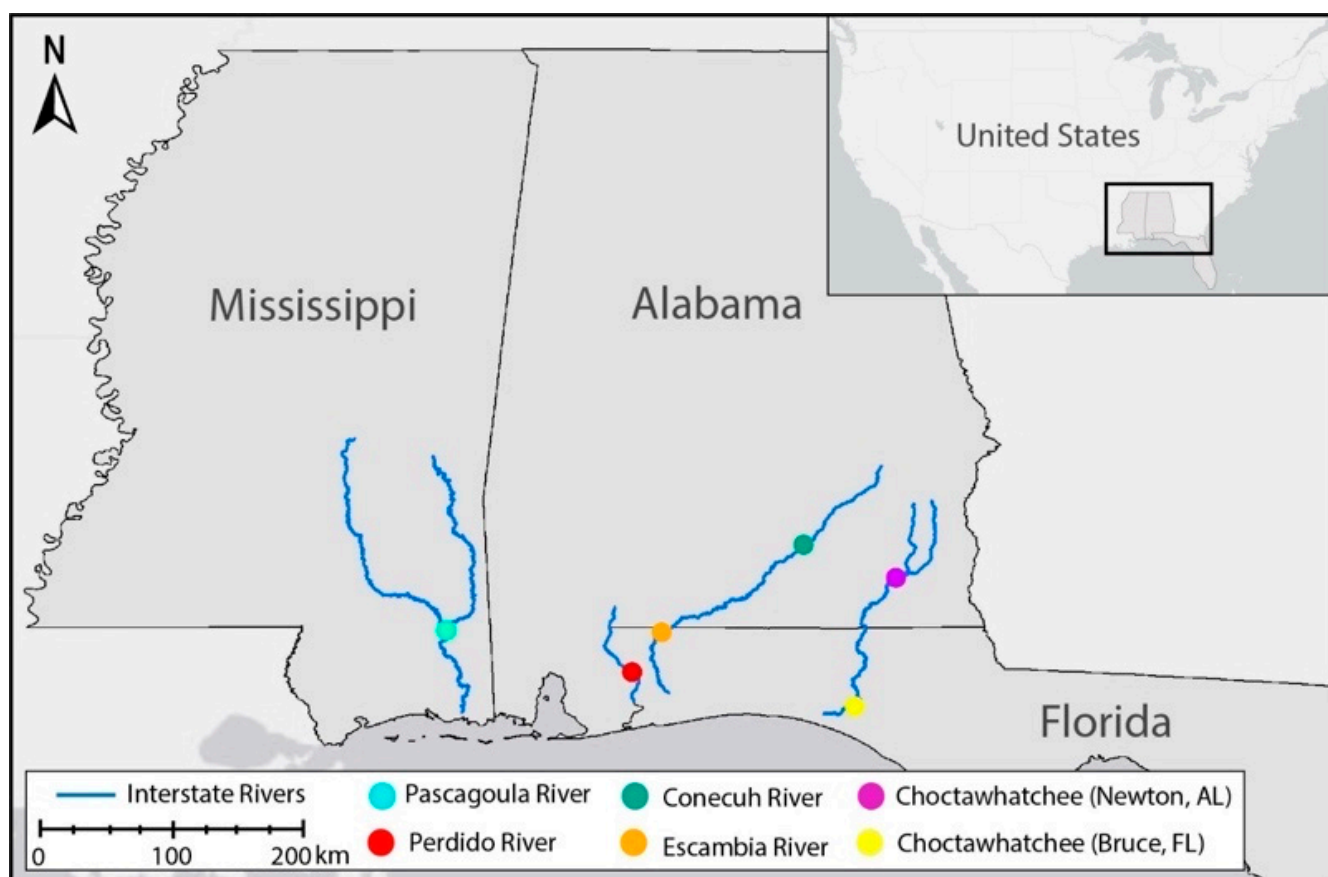


Figure 1. Location map with inset of study location within the overall United States (small black rectangle) and the six United States Geological Survey (USGS) streamflow gages used within the study between the states of Mississippi, Alabama and Florida.

2. Materials and Methods

2.1. Streamflow Data

Streamflow data for five gages near the Alabama-Florida border and one gage near the Mississippi-Alabama border for regional comparison were obtained from the United States Geological Survey (USGS) website, via the National Water Information System (<http://waterdata.usgs.gov/nwis/sw> (accessed on 16 June 2020) [47]. The USGS gages contained minimal missing data and had an acceptable record to calibrate with tree-ring chronologies from the region. The gages presented in this study are located on the Choctawhatchee River (near Newton, AL and Bruce, FL), the Conecuh River, the Escambia River, and the Perdido River (Figure 1; Table 1). These rivers are located in or near the panhandle region of Florida and constitute important streamflow systems in the region. The Conecuh River flows into the Escambia River, and the Choctawhatchee gage in Newton, AL is upstream of the gage in Bruce, FL, making the streamflow patterns in these gages highly correlated. Additionally, the nearby Pascagoula River in Mississippi was investigated for regional comparison. Monthly cumulative flow in million cubic meters (MCM) was used.

Table 1. Descriptions of the United States Geological Service (USGS) streamflow gages used for reconstruction.

Station Name	Station ID	Latitude	Longitude	Drainage Area (km ²)	Period of Record
Choctawhatchee River (Newton, AL)	02361000	31°20'34" N	85°36'38" W	1777	1936–2016
Choctawhatchee River (Bruce, FL)	02366500	30°27'03" N	85°3'54" W	11,355	1931–1982
Conecuh River (Brantley, AL)	02371500	31°34'24" N	86°15'06" W	1295	1938–2015
Escambia River (Century, FL)	02375500	30°57'54" N	87°14'03" W	9886	1935–2018
Perdido River (Barri-neau Park, FL)	02376500	30°41'25" N	87°26'25" W	1020	1942–2017
Pascagoula River (Merrill, MS)	02479000	30°58'40" N	88°43'35" W	17,068	1931–2019

2.2. Tree Ring Chronologies

Seventy-four “standard” TRCs from within and around the Southeastern US were used in our initial analyses. Data for 60 of these were downloaded from the International Tree-Ring Data Bank (<https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring> (accessed on 20 June 2020)) [48], which is maintained by the National Oceanic and Atmospheric Administration (NOAA) Paleoclimatology Program, and an additional 14 records were developed by the authors or provided by other researchers. Chronologies were developed as described in Harley et al. [14]. In addition to year-to-year comparison, all TRCs were shifted forward one year to account for streamflow records correlating with tree ring growth in the following year [49], denoted by a “+1”, and the 74 lagged TRCs were used in analysis for a total of 148 TRC variables.

2.3. Predictor Prescreening Methods

Two prescreening methods were used to identify the most suitable TRCs to use as predictors for the reconstruction models. We selected the spring to early fall (March–October; M–O) period of streamflow to analyze, as it has been found to be optimal for streamflow-TRC correlation in the Southeastern US [14]. During the M–O season, the bulk of streamflow recharge in this region is due to rainfall associated with cold fronts, convective thunderstorms, and tropical cyclone activity [14]. The overlapping time periods for M–O streamflow and all 148 TRCs (t and $t + 1$) were correlated using Minitab, and the TRCs with positive, significant R-values ($p \leq 0.05$) were retained. This initial calibration period stretched from the first year of streamflow data to the earliest end date of an included TRC. As statistically insignificant TRCs were eliminated, the calibration period changed to reflect the end date of the retained TRCs. This correlation was performed repeatedly with retained TRCs while adjusting the calibration period as necessary until it remained stable.

The second pre-screening method involved temporal stability analysis, per Biondi and Waikul [50], which consisted of performing correlation over 30-year moving windows between the various streamflow seasons and the chronologies identified (retained) by the first pre-screening analysis. No chronologies were found to contain negative 30-year correlation values with seasonal flow; therefore, all first pre-screening method retained TRCs were considered and were retained for this analysis. Stability analysis ensures that reliable and practical streamflow reconstructions are generated.

2.4. Reconstruction Methodology

Because all the available TRCs end before the currently available gage data (Table 2), model calibration windows were controlled by the date that streamflow data were first

collected at each gage and the end date of each TRC. The beginning dates of the calibration windows ranged from 1931 to 1942 CE (Table 1), and the end dates ranged from 1983 to 2011 CE (Table 3). The statistical fitness of the TRCs to estimate streamflow was tested using a forward and backward (standard) stepwise regression model using Minitab.

The model adds and removes predictors until all variables not in the model have p -values that are greater than the specified alpha-to-enter value, and when all variables in the model have p -values that are less than or equal to the specified alpha-to-remove value. Following the procedure of Woodhouse et al. [21], the F-level for a predictor chronology had to have a maximum p -value of 0.05 for entry and 0.10 for retention in our stepwise regression model.

Standard statistical measures were used to establish the statistical skill of each streamflow reconstruction [32]. The R^2 value quantified the amount of variance in each model. The R^2 —predicted was calculated in Minitab using leave-one-out-cross-validation, in which a single year or observation is removed when fitting the model.

Table 2. Tree-ring chronologies (TRCs) retained in streamflow reconstruction models.

Code	ITRDB Code	Chronology	State	Species	Chronology Length
CHK _{EW}	FL001	Choctawhatchee Earlywood [33,51]	FL	TADI	920–2014
CHK	FL001	Choctawhatchee Total Ringwidth [33,51]	FL	TADI	920–2014
EBE	GA003	Ebenezer Creek Total Ringwidth [52]	GA	TADI	990–1985
OCM ₁	GA004	Ocmulgee River Total Ringwidth +1 [53]	GA	TADI	1203–1985
SKY	MS003	Sky Lake Swamp Total Ringwidth [54]	MS	TADI	1238–2010
PNC ₁	TN005	Piney Creek Total Ringwidth +1 [55]	TN	QUAL	1652–1983
SUW	FL005	Suwannee River Total Ringwidth +1 [56]	FL	QULY	1725–1993
IOL ₁	TBD	Iola Lake Total Ringwidth +1 [57]	FL	NYOG	1867–2011
PAS	MS002	Pascagoula River Total Ringwidth [58]	MS	TADI	1540–2014

Note: “+1” = tree ring growth in the following year; TADI = *Taxodium distichum* L. Rich. (bald cypress); QUAL = *Quercus alba* L. (white oak); QULY = *Quercus lyrata* Walter (overcup oak); NYOG = *Nyssa ogeche* L. Ogeechee Tupelo (ITRDB = International Tree Ring Databank [51]).

As a result, the prediction errors are independent of the predicted value at the removed observation [59]. The Variation Inflation Factor (VIF) indicates the extent to which multicollinearity is present in a regression analysis. Generally, a VIF value close to 1.0 indicates low correlation between predictors and is ideal for a regression model [60]. The Durbin–Watson (D–W) statistic was used to analyze the autocorrelation structure of model residuals [61]. The sign test, a nonparametric procedure to count the number of agreements and disagreements between instrumental and reconstructed flow, was used for additional model validation.

After reconstruction models were established, quantile mapping bias correction was performed via the “RQUANT” method in the qmap package in R [62,63], as described in Robeson et al. [64]. The bias-corrected reconstructions for the three downstream gages (Choctawhatchee at Bruce, Escambia, and Perdido) were then standardized for comparison.

For comparison to a river system outside of the AL-FL intrastate system, and to better understand the potential hydroclimatic drivers throughout the region, a streamflow reconstruction was also performed following the same techniques for the Pascagoula River gage in Merrill, MS west of our study area (Figure 1; Tables 1 and 2). Like all other reconstructions in this study, streamflow reconstructions for the Pascagoula River were standardized and bias corrected, and therefore made comparable to the recent observed period (post-1980s CE), as well as the reconstructions of intrastate rivers along the AL-FL border.

3. Results

After correlation, the TRCs containing positive, significant R-values ($p \leq 0.05$) were retained. The number of retained TRCs varied by streamflow gage, but out of the original 148 TRCs, 14 TRCs were retained in the Perdido River, 17 were retained in the Choctawhatchee River (at Bruce, FL), 20 were retained in the Escambia River, and 21 were retained in the Choctawhatchee River (at Newton, AL) and Conecuh correlation analyses. Following the stability analysis (30-year window), the final number of chronologies introduced into the stepwise linear regression model remained the same, ranging from 14 to 21.

For all streamflow gages, the best calibration models and reconstructions (based on the length of the record and overall statistical skill) were chosen (Table 3). The calibration models listed in Table 3 were statistically skillful ($R^2 \geq 0.50$). The D–W test for autocorrelation in the residuals from the regression showed that the autocorrelation was not significant for any of the models, indicating that the residuals were random, and the models were appropriate [65]. VIF values for all models were within the acceptable ranges (1.0–1.2) and the sign test results were insignificant ($p \geq 0.10$) for all the calibration models, indicating that the models were balanced with no significant bias.

TRCs retained by the calibration models were distributed across the Southeast, and five of the eight retained TRCs were *Taxodium distichum* (L.) Rich. (bald cypress; Table 3). As the longest-lived tree species in eastern North America, *T. distichum* has been shown to provide a valuable annual archive of multi-millennial paleo-hydroclimate conditions [3,8,9,14,29,31], and thus is ideal for developing these long reconstructions. Three TRCs were retained in the Choctawhatchee (Newton), Conecuh and Escambia River models, and two were retained by the Choctawhatchee (Bruce) and Perdido River models.

Table 3. March–October streamflow reconstruction statistics and standard tree-ring chronologies (TRCs) used in each model.

Gage	Reconstruction Period	R^2 (p)	R^2	R^2_{adj}	VIF	D–W	Sign Test +/-	TRCs Retained
Choctawhatchee at Newton	1203–1985	0.48	0.56	0.54	1.0	2.2	26/24	EBE, CHK, OCM ₁
Choctawhatchee at Bruce	1238–1983	0.47	0.51	0.49	1.2	2.3	24/28	SKY, CHK
Conecuh	1652–1983	0.41	0.51	0.49	1.1	2.1	23/23	PNC ₁ CHK _{EW} , OCM ₁
Escambia	1725–1993	0.48	0.57	0.55	1.2	1.9	30/29	CHK _{EW} , SUW, SKY
Perdido	1867–2011	0.43	0.50	0.49	1.1	2.0	39/31	CHK _{EW} , IOL ₁
Pascagoula	1238–1985	0.42	0.50	0.48	1.1	2.1	31/24	SKY, CHK _{EW} , OCM ₁

Note: “+1” = tree ring growth in the following year; CHK = Choctawhatchee Ringwidth; CHK_{EW} = Choctawhatchee Earlywood; EBE = Ebenezer Creek; IOL₁ = Iola Lake +1; OCM₁ = Ocmulgee River +1; PNC₁ = Piney Creek; SKY = Sky Lake; SUW = Suwannee River; R^2 = Variance in the data that is explained by the model, R^2 (p) = R^2 (predicted) is a measure of how well the model predicts new observations, R^2_{adj} variance explained adjusted for multiple predictors; VIF = Variance Inflation Factor is a measure of the correlation between predictors, D–W = Durbin–Watson statistic is a measure of autocorrelation in residuals.

All five streamflow gages demonstrate comparable patterns in their reconstructions, indicating a common climatic pattern in the AL-FL region (Figures 2a–c and 3). At all four gages reconstructed to the early 1800s, a notable pluvial event was observed in the reconstruction ca. 1830 CE, followed shortly after by a severe drought in the mid-1800s. All five reconstructions end prior to the end of the observed records and cannot be compared to more recently observed data without bias correction [64]. Therefore, the initial streamflow reconstruction values were bias-corrected. The bias-corrected data for the downstream gages along the rivers located in Florida (Choctawhatchee at Bruce, Escambia, and Perdido) were then standardized such that they could be compared against each other (Figure 3; [63]).

The Conecuh and Choctawhatchee at Newton gages were not included in this analysis because the Conecuh streamflow is highly correlated with the Escambia gage, and the Choctawhatchee at Newton streamflow is highly correlated with the Choctawhatchee at Bruce gages. The three downstream gages followed a very similar pattern over the overlapping 150 year period. Despite a recovery in streamflow in the 1990s in the Perdido River, all three rivers appear to be in a drought state now, as the streamflow has been below average for the last 20–30 years (Figure 3a,b).

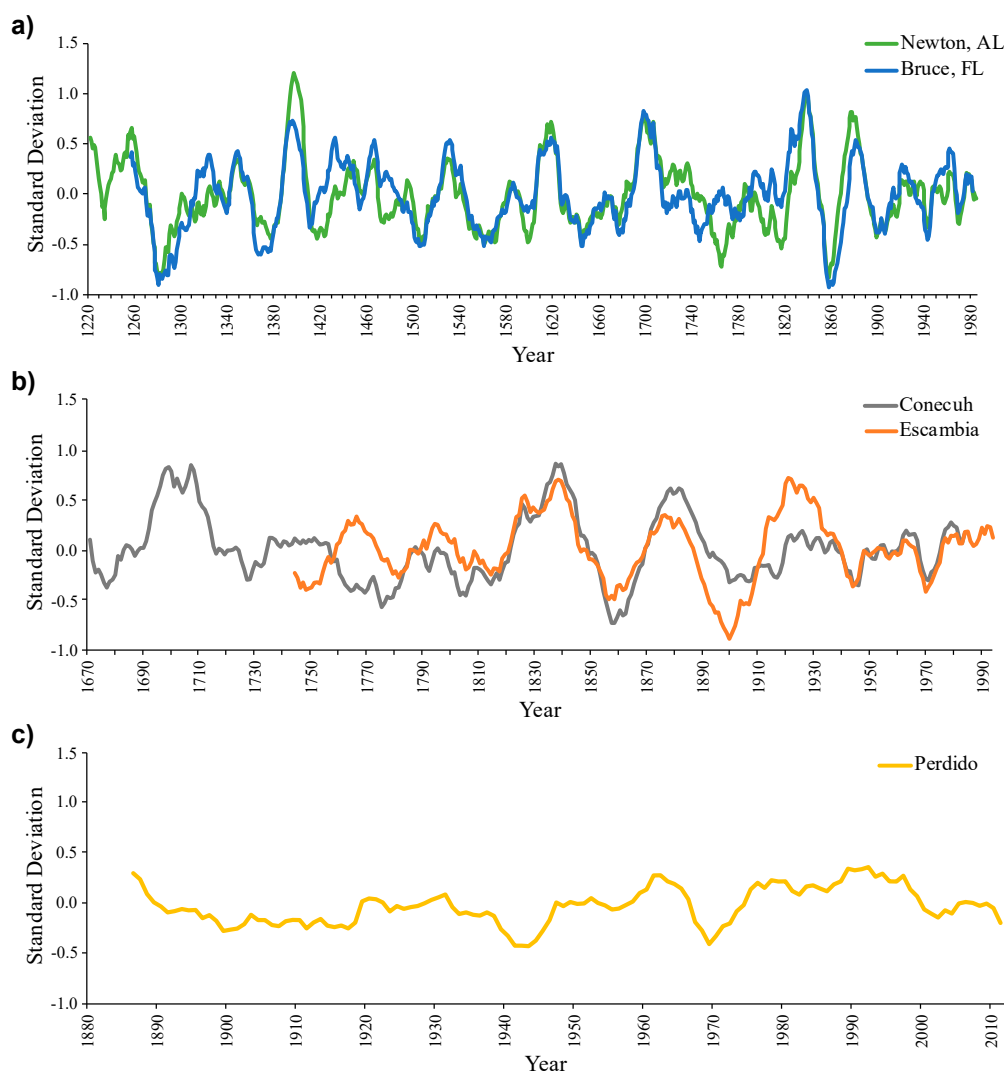


Figure 2. Standardized streamflow reconstructions for the (a) Choctawhatchee River at gages in Newton, AL (1222–1885) and Bruce, FL (1257–1882), (b) Conecuh River (1671–1883) and Escambia River (1744–1993), and (c) Perdido River (1885–2011). All datasets have been smoothed with a 20-year-end-year running mean. For full time scale see Figure A1.

For comparison, the Pascagoula river gage near Merrill, MS is presented relative to the three other streamflow reconstructions for the AL-FL rivers (Figure 3). Unlike the rivers along the AL-FL border, the Pascagoula River has demonstrated a recovery in streamflow over the last 20–30 years (Figure 3), indicating a potential divide in the hydro-climatic conditions east and west of the MS-AL border.

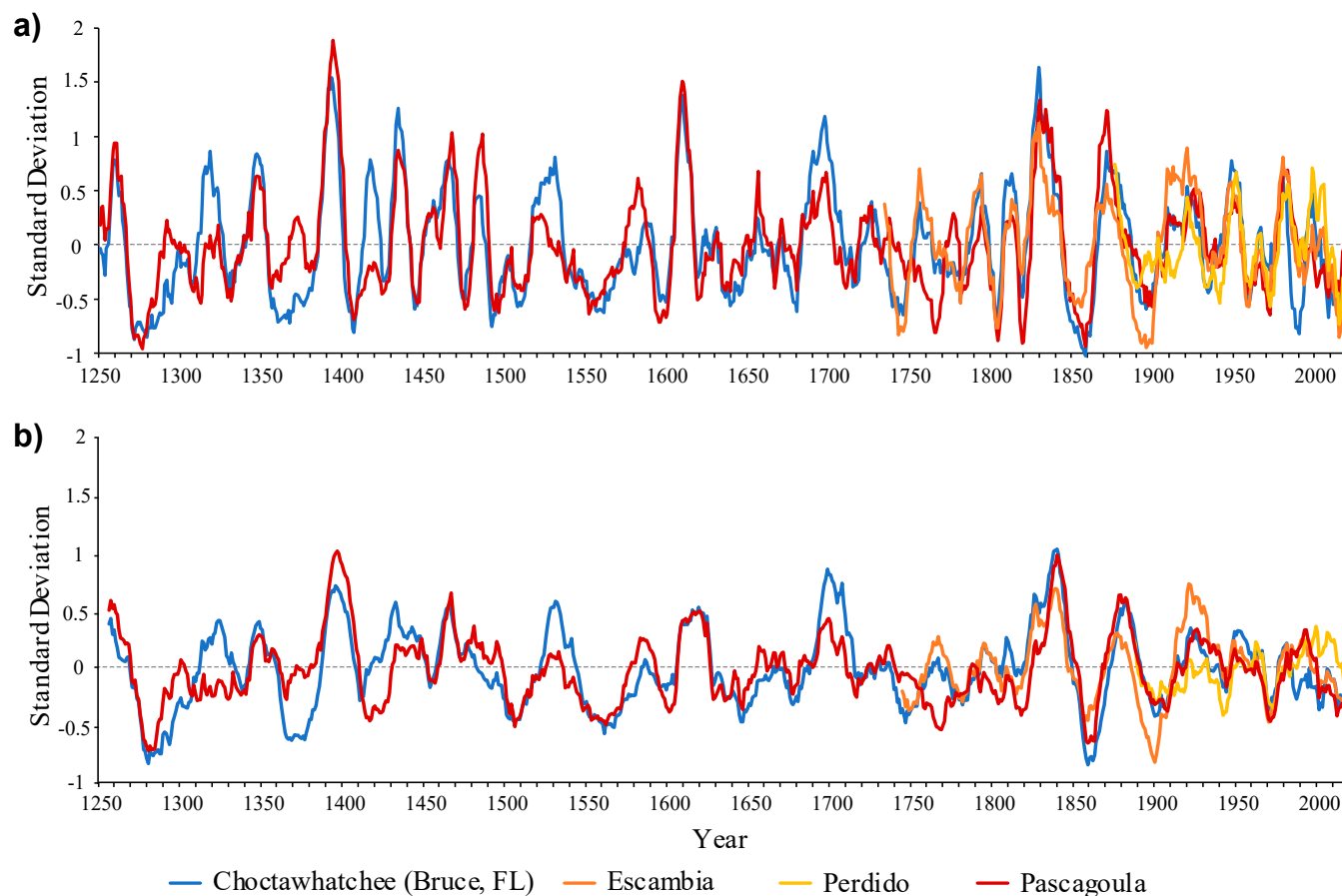


Figure 3. Bias corrected and standardized reconstructed and observed streamflow for the Choctawhatchee, Escambia, Perdido, and Pascagoula rivers (1238–2019) smoothed with a (a) 10-year end-year filter (1247–2019) and (b) 20-year end-year filter (1257–2019).

4. Discussion

Clear patterns in hydroclimatic regimes emerge from the streamflow reconstructions in each of these different rivers, as all five of the reconstructions indicate similar hydroclimatic extremes within the paleo-record. As indicated in the bias-corrected 10- and 20-year filtered reconstruction data (Figure 3a,b) periods of multi-year pluvial activity are indicated in the 1390s, 1600s to 1610s, 1690s to 1700s, 1820s to 1840s (including the 1830 CE event) and 1860s to 1880s. While streamflow reconstructions that extend back to the early 1300s are limited within the region, historical and reconstructed records from rivers in Florida and Georgia show that the late 17th century and the early and late 19th century experienced intense pluvial periods [12,14,30,34].

While periods of intense pluvial events are clearly present within the reconstructions, multi-year droughts are indicated throughout the record and are validated by other similar findings throughout the region. Two of the more extreme periods of dryness and drought within the record occur between ~1840–1860 and ~1890–1910. The period from 1840–1860 is identified regionally [14,66] and is of particular interest due to the abrupt shift in hydroclimatic conditions from intense drought to extreme moisture and pluvials in the later 1860s. The subsequent period of drought from ~1890–1910 marks a period of

dryness noted in multiple hydroclimate reconstructions throughout the Southeastern US [3,14,34]. Climate models presented in Herweijer et al. [67] indicate that this period of extreme drought is likely a response to cool tropical Pacific sea surface temperature (SST) forcing.

The recent drought (since ca. 2000 CE) in the Choctawhatchee, Escambia, and Perdido Rivers ranks as one of the most severe in the reconstructed paleo record. At each gage, we identified a recent 10-year drought period, and by ranking percentiles we determined the top 5%. The 2008 CE (1999–2008) drought in the Choctawhatchee River and the 2015 CE (2006–2015) and 2016 CE (2007–2016) droughts in the Escambia and Perdido Rivers ranked in the top 5% of the driest periods in the reconstruction, only exceeded by droughts in the mid- and late-19th century. When examining the 20-year filtered results, the Conecuh, Escambia, and Perdido reconstructions again display a notable decline since 2000 CE, with several 20-year drought periods ending since 2000 in the top 10% of the driest periods.

This period of multi-decadal streamflow decline has been observed throughout other states in the Southeastern US and appears to be associated with the confluence of multiple La Niña events (4) during a warm phase of the Atlantic Multidecadal Oscillation (AMO), with an inverse relationship between mid-Atlantic SST and streamflow over the same period [46]. Multiple studies have shown the association between Southeastern US water resources and AMO, ENSO, and PDO conditions [1,36–43], indicating the influence of both high and low frequency climate teleconnections within the region.

Interestingly, the Pascagoula River displays a strong recovery in streamflow during the 2000s when compared to the AL-FL interstate rivers in both the 10-year and 20-year end-filter analyses. This finding is consistent with Ho et al. [68], which suggests that a shift in climate exists along the Alabama-Mississippi state border. It is possible that increased moisture is found in the western regions of the Gulf of Mexico's coastal rivers compared to the eastern regions, as the eastern regions are more likely to be influenced by the western flank of the North Atlantic subtropical high (NASH; [69,70]). Further work investigating the hydroclimatic drivers and teleconnections is needed to elucidate the spatial variability in streamflow conditions across the Northern Gulf of Mexico. The end dates of these reconstructions reaffirm the need for new and updated TRCs in the studied region. To develop strong correlations and reconstruction models and to better predict streamflow variability, it is imperative that the International Tree Ring Databank (ITRDB) be continually updated and expanded. The new and updated chronologies developed and used within this work are part of an ongoing effort by multiple research teams to update and add new chronologies to the ITRDB [71–73]. Additionally, most reconstructions currently published in the region do not extend past the early 2000s [14,30]. For example, a reconstruction of the Suwannee River in Florida, east of our study area [14], demonstrated evidence of low streamflow in the Suwannee River since 2000, but the article did not discuss data more recent than 2005 CE. Thus, the Suwannee reconstruction cannot be compared to the 2015 CE drought observed in this study. Similarly, Pederson et al. [30] reconstructed drought in the Apalachicola-Chattahoochee-Flint river basin. This study demonstrated evidence of drought since 2000, but the reconstruction ended in 2010, so the period from 2010–2019 is not observed.

5. Conclusions

A multi-decadal decline in streamflow has been observed throughout the Southeastern US since the start of the 21st century. In this work, we show that relative to our nearly 800 year reconstructions of streamflow in the Choctawhatchee, Escambia, and Perdido Rivers, the last 20 years have had droughts ranking among some of the most severe in the reconstructed paleo record. In the 10-year filtered data, drought periods in the Choctawhatchee (1999–2008), the Escambia (2006–2015) and the Perdido Rivers (2007–2016) ranked among the driest periods (top 5%) in the reconstruction, exceeded only by historic droughts in the 19th century. Similarly, in the 20-year filtered results, several streamflow

reconstructions show that declining streamflow and drought over the past two decades have resulted in one of the lowest flow periods in the record (top 10%). Given that the streams in this study have been identified by the USGS as “unimpaired” and have minimal anthropogenic impacts (such as consumptive extraction), our findings suggest that the rivers in this work are experiencing significant climate-driven declines in streamflow. These results are consistent with the findings of other studies throughout the southeastern US, which show this multidecadal decline associated with the interactions of both high- (La Niña) and low- (AMO, PDO) frequency climate teleconnections [14,36–43,46].

Knowledge of previous years’ droughts and pluvial events is critical when making water policy decisions. With the combined stressors of population growth, interstate water wars, and climate change, it is imperative for Florida water managers and planners to have a full understanding of hydrologic parameters in the region. Instrumental observations for the five streamflow gages used in this study began in the 1930s–1940s CE, but the statistically skillful reconstructions presented in this study provide insight into streamflow as far back as the 1200s CE. We recommend additional paleo-reconstructions of interstate and coastal rivers in the southeastern United States be conducted to provide more insight into historical climate patterns and associated climate drivers in this region.

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Data Availability Statement: All streamflow data are available from the United States Geological Survey via the National Water Information System (<http://waterdata.usgs.gov/nwis/sw>) and all tree-ring data are available from the International Tree-Ring Data Bank (<https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring>).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A

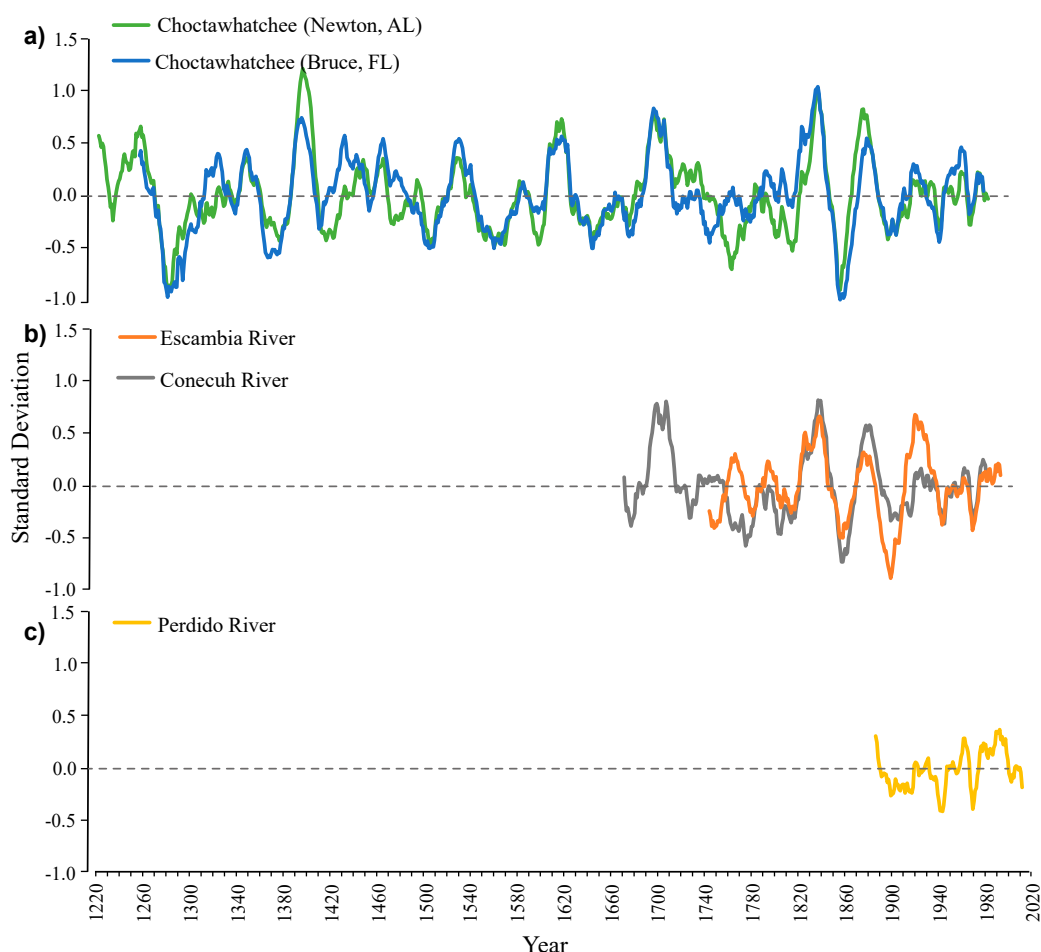


Figure A1. Comparison over the full reconstruction period of standardized streamflow reconstructions for the (a) Choctawhatchee River at gages in Newton, AL (1222–1985) and Bruce, FL (1257–1982), (b) Conecuh River (1671–1983) and Escambia River (1744–1993), and (c) Perdido River (1885–2011). All datasets have been smoothed with a 20-year-end-year running mean.

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