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Exploring the potential for a multi-decadal midsummer streamflow reconstruction of the upper Samalá river basin in Guatemala using an *Abies guatemalensis* tree-ring chronology

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ABSTRACT

The Samalá River in western Guatemala is critical for sustaining diverse agricultural production systems, from staple crop production in the upper basin to sugar cane in the lowlands. The streamflow from the Samalá River also supports hydroelectric power generation within the basin. The watershed is home to more than a hundred settlements including cities, towns, and villages, some of which have experienced extreme hydrological events, including destructive flooding from the river. However, the Samalá River streamflow record, only 38 years in length (1979–2016), is too short to assess the full range of hydrological variability for this economically important region, including Guatemala's second largest city –Quetzaltenango. This paper presents a tree-ring based reconstruction of mean August streamflow for 125 years (1889–2013). Our results suggest that annual tree-ring width measurements from *Abies guatemalensis* are correlated with monthly mean streamflow records in the upper Samalá River basin. This association seems to be modulated in part by variability in the ENSO 3.4 region in the Pacific Ocean, suggesting decreased streamflow during the warm events of the sea surface temperature in the Pacific Ocean. The record indicates that single year events of low streamflow dominate the record. Nevertheless, a period of up to 8 consecutive years below-average streamflow is shown in the record between 1905 and 1912. Overall, this extended record of streamflow suggests that tree-ring studies in the area have the potential to provide useful inputs in the future that can be utilized by stakeholders and decision-makers within the Samalá watershed involving the management of discharge for crop irrigation, hydropower production, and disaster mitigation.

1. Introduction

Central America has lost an estimated US$9800 million to drought in the past 30 years, half of which was associated with the agricultural sector (GWP 2016). In many regions of Guatemala, staple and cash crop production have been negatively affected by extreme precipitation and streamflow events (Soto et al., 2015). Other important economic sectors like hydropower generation continue to be affected by these extremes. Unfortunately, hydroclimatic records in Guatemala are scarce and extend only a few decades (Anchukaitis et al., 2014; Magrin et al., 2014; Pons et al., 2017). The scarcity of hydroclimatic data in Guatemala, represents a limiting factor in assessing climate variability and the identification of hydrological trends in the region (Anchukaitis et al., 2013; Magrin et al., 2014; Donatti et al., 2017; Hannah et al., 2017). In addition to extreme hydrological events, increases in temperature across the country pose additional challenges to water management for crop production and hydroelectric power generation due to potential increases in evapotranspiration and reduced runoff (Magrin et al., 2014; INSIVUMEH 2018; Shi et al., 2022). According to Guatemala's Meteorological Institute, the mean annual temperature in Quetzaltenango, Guatemala's second largest city located in the upper section of the Samalá River watershed, has already experienced an increase of 1.4 °C

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in the last decades (INSIVUMEH 2018). These increasing temperatures in high mountainous regions of Guatemala where rain-fed agriculture accounts for the livelihoods of hundreds of thousands of residents might translate into increased potential evapotranspiration and a subsequent reduction in water availability for irrigation and power generation. However, little is known about the whole range of natural and anthropogenic hydroclimatic variability in this region due to a lack of long-term instrumental records. This lack of hydrological records can in part be alleviated using tree-ring records to assess historical streamflow variability (Anchukaitis et al., 2013). This information can in turn be used for decision-making processes related to water management including the design of water policies and infrastructure (Woodhouse, 2001; Loáiciga, 2005; Woodhouse and Lukas, 2006; Meko et al., 2011; Mundo et al., 2012; Malevich et al., 2013; Villanueva Díaz et al., 2014). In this study we use a tree ring chronology from the Guatemalan fir *Abies guatemalensis* collected in Quetzaltenango to assess the potential of the species to reconstruct the hydrologic variability of the upper Samalá River streamflow. In addition, we explore the potential influence of El Niño-Southern Oscillation (ENSO)on the hydrology of the basin. These associations have been reported at other sites in Guatemala's Western Highlands (Anchukaitis et al., 2014). The information generated here could help decision makers from different sectors, including those associated with agriculture and hydroelectric productivity, to understand the current influence of climate variability to the streamflow of the Samalá River.

1.1. Study site

The Samalá River watershed covers 1510 km^2 across the departments of Totonicapán, Quetzaltenango, Retalhuleu, Sololá, and Suchitepéquez (Fig. 1). An estimated 725,000 people settled in 35 *municipios* inhabit the watershed (Picado Traña et al., 2016). Located between Santiaguito and Santo Tomas volcanoes, it follows the Zunil Fault Zone to the south (Bennati et al., 2011). The streamflow of the Samalá River is regulated in the middle section of the watershed by a nested system of 5 dams with a total capacity of 102.58 MW equivalent to around 10 % of Guatemala's hydropower generation (Alvarado et al., 2015; MEM 2018). The average annual precipitation within the watershed ranges from around 900 mm at both the higher elevations of 3000 m and coastal zones and is highest in the middle altitudes near San Felipe Retalhuleu with up to 4000 mm. Precipitation is characterized by a bimodal regime with peaks occurring in June and September, and a pronounced Midsummer Drought (MSD) between July and August (INSIVUMEH 2018; Anderson et al., 2019). The average annual temperature ranges from 10 °C at the highest elevation of 3000 m to around 25.5 °C in the coastal plains (INSIVUMEH 2018). Geologically, the upper section of the watershed comprises a minimum proportion of cretaceous sedimentary rock towards Totonicapán, some quaternary volcanic rocks near the Santa Maria and Santiaguito volcano complex, tertiary volcanic rocks surrounding the watershed edges, and vast pyroclastic deposits encompassing most of the central area of the watershed where Quetzaltenango City rests (Bucci et al., 2015).

The Samalá River has been identified by local communities as essential for subsistence and cash-crop agriculture, especially in the Almolonga and Zunil valleys (Falkowski, 2000; De Urioste-Stone et al., 2013). Other important economic sectors within the watershed include coffee production in the piedmont, sugar cane in the lowlands, and hydroelectric power production along the watershed. The agricultural production in the upper Samalá watershed (mainly vegetables, maize, and flowers) is supported by the Chinimá River in Almolonga (a tributary of the Samalá River), and the Samalá River in Zunil. Both perennial rivers enable irrigation of vegetables year-round through a network of pipelines and human-made channels carved in the ground (Falkowski, 2000). The Almolonga sub-basin has been historically one of the main areas for vegetable production in western Guatemala (Arbona, 1998).

2. Materials and methods

2.1. Tree-ring data

The Guatemalan fir (*Abies guatemalensis*) core samples were used to create an extended record of hydroclimatic variability. The species is widely distributed across the high mountain range of western Guatemala from Huehuetenango and San Marcos departments in the west it extends to El Progreso and Jalapa departments in Guatemala eastern areas ((Instituto Nacional de Bosques-INAB, 2019). The species has been used in Guatemala's western highlands before to reconstruct precipitation showing reliable cross-dating and sensitivity to climate (Anchukaitis et al., 2013, 2014). Within the Samalá River watershed the species can be found in the Quetzaltenango and Sololá departments from 2700 to 3600 m.a.s.l. Two to three increment core samples from 60 trees were collected from stands in the Kanchej forest area (Fig. 1). Sampling followed methods outlined by Cook and Kairiukstis (1990). A first set of samples was collected in the boreal summer of 2014 and a second one in the boreal summer of 2015. Samples were dried, mounted, sanded and crossdated following standard procedures (Stokes and Smiley, 1968). Some samples were excluded because they contained sections of growth suppression, which prevented measurements of ring widths (Stahle et al., 2011). The final chronology was built using 30 dendrochronological samples from 21 trees. The samples were measured to 0.001 mm precision using a Velmex measuring table and the MJ2X software. The crossdating and measurement were verified using COFECHA (Holmes, 1983). After the verification, the program ARSTAN (Cook, 1985) was used to standardize and detrend the ring-width series using a 50-year smoothing spline to 50 % amplitude of the individual series length. The standard chronology (Cook, 1985) was used in this analysis to preserve the autoregressive structure of the time series to evaluate climate variability (Razavi and Vogel, 2018). We assessed the common signal in the tree-ring chronologies using the inter-series correlation and expressed population signal (EPS) statistics and found the chronology to be robust between 1889 and 2014.

2.2. Climate and discharge records

Climate records were provided by the National Meteorological Institute of Guatemala (INSIVUMEH) and by the National Institute of Electrification (INDE). The data from Labor Ovalle weather station located in Quetzaltenango (Fig. 1) was provided by INSIVUMEH for the period 1971–2015. The station is located 11 km from the sampling site. The data from the Zunil and Santa María weather stations and the El Tunel gauge was provided by INDE for the period 1980–2015 and 1979–2015 respectively (Fig. 1), located at 3 km form the sampling site. We also used climate data from the Climate Research Unit (CRU Ts 4.01) dataset (Harris and Jones 2017) and the ERA5 Reanalysis product (Copernicus Climate Change Service (C3S), 2019) to further extend the correlation analysis.

The Samalá River streamflow records were provided by the National Institute of Electrification (INDE) from the year 1979–2017. The gauge collecting the streamflow data is located in the outlet of the Upper Samalá watershed section before the Santa María dam (Fig. 1). Streamflow outliers were detected in the time series and treated using the Median Absolute Deviation (MDA) method for replacement (Leys et al., 2013). Streamflow series were then normalized using a Box Cox transformation for each month (Box and Cox, 1964) and passed normality tests using the Anderson-Darlin test (Stephens, 1974).

2.3. Climatic response of the chronology

We used the *seascorr* software (Meko et al., 2011) to evaluate correlations and partial correlations between the normalized discharge data series from the El Tunel gauge and the tree ring width (RW) chronology from 1-month to 6-months period starting with July and finishing in

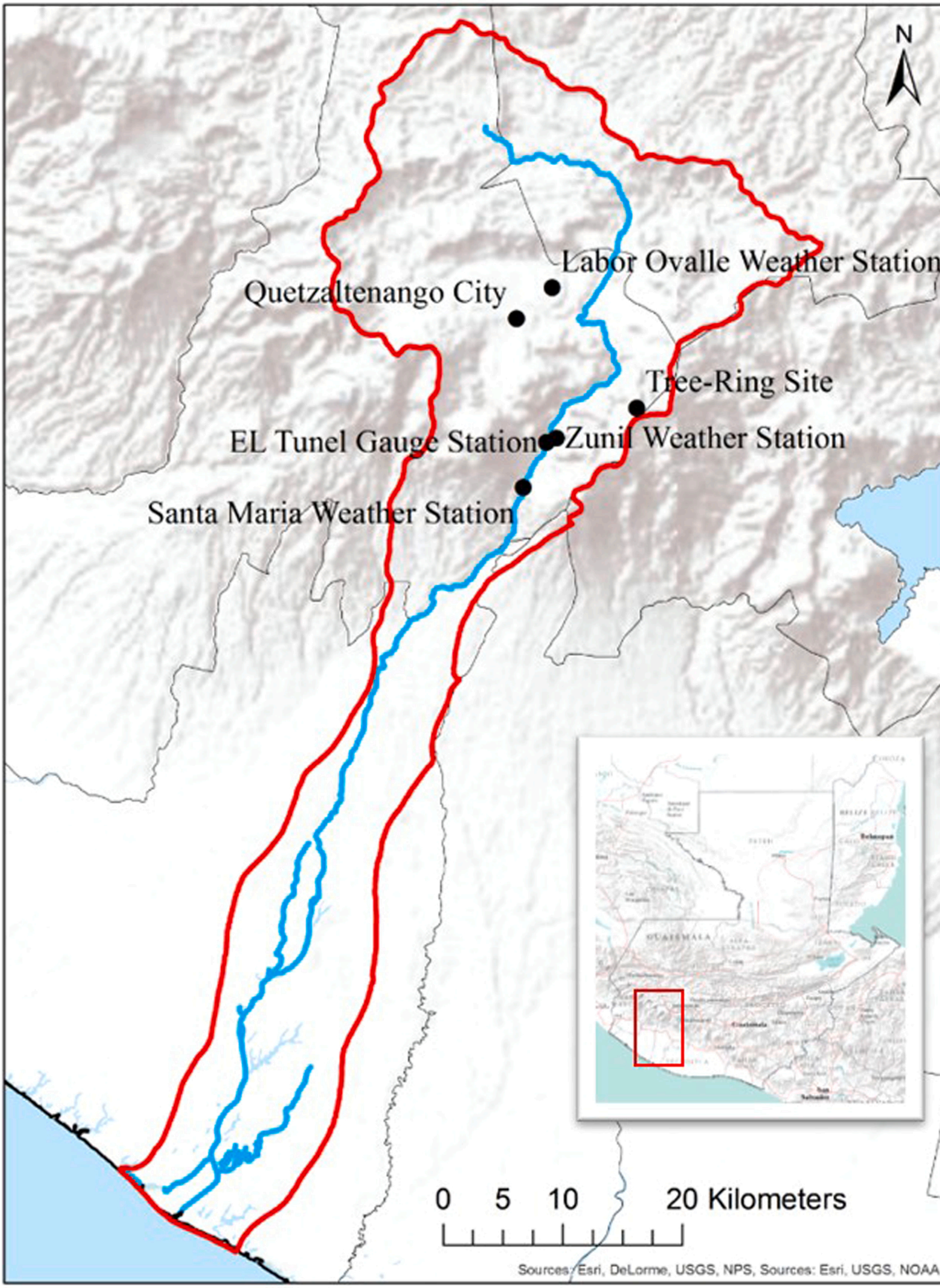

Fig. 1. Location of Samalá River Basin in Guatemala and distribution of weather stations, gauges, and tree sampling site.

December.Similarly, we assessed the partial correlations with temperature. The timescale for the evaluation included June of the previous year to August of the current year. This time window was based on previous assessments on the climatic signal of the species in Guatemala (Anchukaitis et al., 2013, 2014). The months included in this period incorporate the mid-summer drought, a period of rainfall lessening modulated in part by the Caribbean Low-Level Jet (CLLJ) during July-August (Polzin et al., 2015). This lessening of the precipitation has serious implications for agriculture in Guatemala (Anderson et al., 2019).

Additionally, we compared the chronology (RW) against August regional precipitation and runoff from the CRU dataset and ERA5 reanalysis respectively and compared an extended period beyond the instrumental data back to 1950 to evaluate the association between the Oceanic Niño Index (ONI) against observed and reconstructed streamflow records. The ONI index reflects the oceanic contribution to ENSO and is calculated as a running 3-month sea surface temperature anomaly in the Niño 3.4 region in the east-central Pacific Ocean (Glantz and Ramirez, 2020).

2.4. Reconstruction

The extremely short period of overlap of 1979–2013 (35 years) between instrumental gauged discharge and our tree-ring data provided a challenge to develop a well calibrated-verified reconstruction. After determining the target reconstruction season, we used a power transform (p = 0.26) to reduce the high positive skew in discharge to 0. To develop our reconstruction, we used a Bayesian Regression model to generate an ensemble of 100 reconstructions using a leave-10-out at random approach to reconstruct streamflow (y_t) in year t, as function of an intercept, slope, and predictor vector X_t (Devineni et al., 2013; Rao et al., 2018).

$$y_t|\alpha, \beta = \alpha + \beta * X_t + \varepsilon_t$$

with non-informative priors modeled as

$$\alpha \sim N\left(0, 10^4\right) \text{and} \beta \sim N\left(0, 10^4\right)$$

To evaluate the fidelity of our reconstruction, we used the following metrics: square of the Pearson correlation, validation period reduction of error (VRE), and validation period coefficient of efficiency (VCE) that is equivalent to the Nash-Sutcliffe efficiency test (Nash and Sutcliffe, 1970; Cook et al., 2010). The calibration period coefficient of multiple determination (CRSQ) and the validation period square of the Pearson correlation (VRSQ) were calculated on the 25-year calibration and 10-year validation period respectively. The final reconstruction was calculated as the median of all 100 model iterations. The presence of periodicities in the reconstructed streamflow was analyzed using *seascorr* software (Meko et al., 2011) and then compared to MEI and ONI ENSO indices.

3. Results and discussion

3.1. Climatic response of the tree ring width chronology

The reported interseries correlation and mean sensitivity of our chronology are 0.447 and 0.273 respectively (Fritts, 1976; Holmes, 1983). The mean segment length for our subset of samples is 107 years. Our initial analysis using instrumental data suggests a strong statistically significant correlation ($p < 0.01$) between the El Tunel discharge from August and the total ring width chronology (RW) for the common period (1982–2014) as seen in Fig. 2. No statistically significant correlation was found between the series and mean temperature.

3.2. Reconstructed august streamflow

The timeseries of spatially averaged precipitation (1950–2015), instrumental observations of August El Tunel discharge (1975–2015) and reconstructed El Tunel discharge (1950–2015) are shown in Fig. 3. Additionally, we include a comparison with the ONI index between 1950 and 2019. We found that both the instrumental discharge and reconstructed discharge are positively and significantly correlated ($p < 0.01$) with CRU regional precipitation in August (Observations vs CRU r = 0.72, 1979–2015; Reconstructions vs CRU r = 0.33, 1950–2013).

3.3. Streamflow and ENSO associations

We also found significant negative relationships between ENSO and both observational and reconstructed discharge (Observations vs ONI r = −0.51, 1979–2015; Reconstructions vs ONI r = −0.44, 1950–2013). This is consistent with the negative relationship between ENSO and regional precipitation in August (CRU vs ONI r = −0.55, 1950–2015, see Rogers, 1988; Waylen et al., 1994; Dettinger et al., 2000; Rice and Emanuel, 2017).

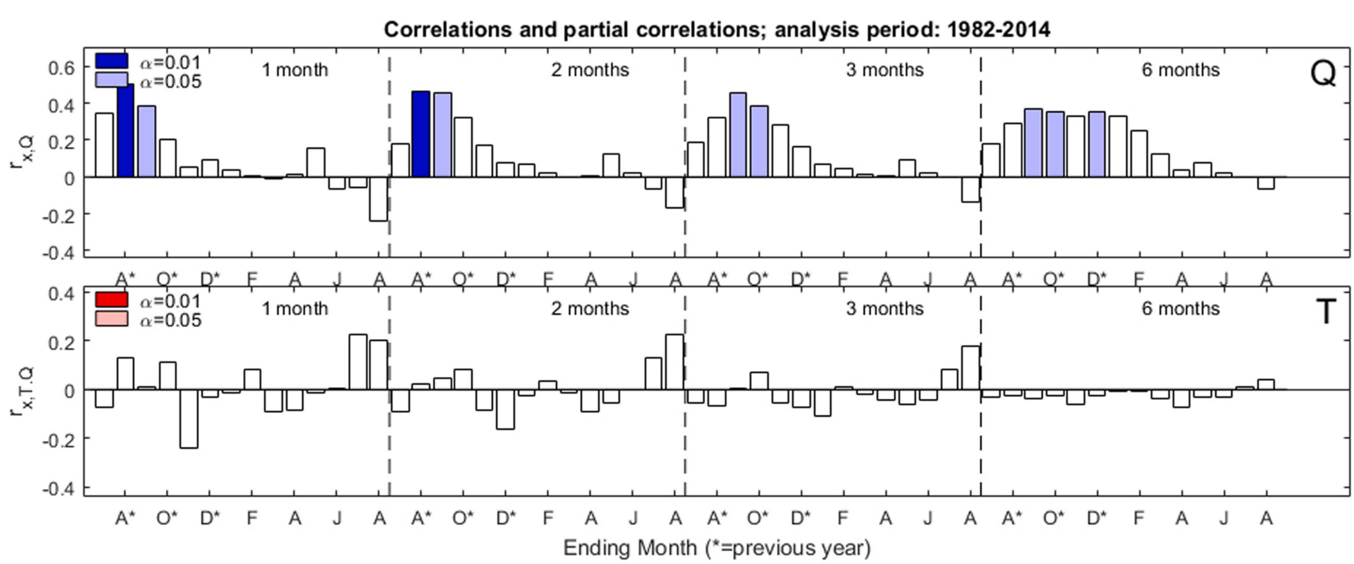

Fig. 2. Correlations and partial correlations for the Kanchej (RW) chronology against discharge (Q) and temperature (T) respectively for 1-month to 6-month period (Meko et al., 2011).

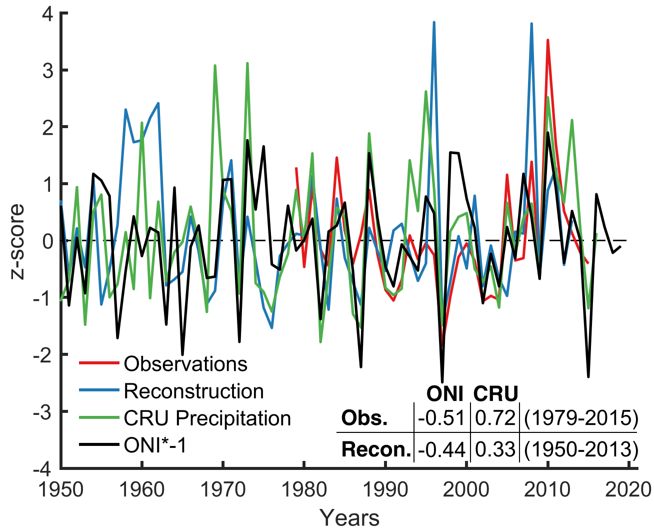

Fig. 3. Observed (red) and reconstructed (blue) discharge time series (Z-scores) against CRU precipitation (green) and ONI-1 (black) timeseries.

The total August discharge variance explained by our reconstruction (square of the Pearson correlation) is 17.63 %. The VRE, and VCE resulted in 0.23 and 0.09 respectively, suggesting the reconstruction performed better than a random estimate of the mean (Cook et al., 1999; Wahl and Ammann 2007). The analysis of the calibration and verification shows a CRSQ (23.86 %) and VRSQ (32.53 %) respectively (Fig. 4).

Our exploratory assessment suggests that there is an association -albeit modest- between the tree ring width and streamflow records during a critical month of the Midsummer Drought period. August streamflow represents a critical source for both agriculture and hydropower generation within the Samalá basin because it is between July and August when the MSD shows an abrupt reduction of rainfall within the rainy season. The extended record beyond the instrumental data into the CRU precipitation data series suggests that there is a coherent spatial and temporal signal between precipitation for the month of August and the discharge for the same month (Fig. 5). Although ENSO and streamflow are linked via precipitation (Rice and Emanuel, 2017), there are many other potential factors affecting the magnitude of this association. This can include forest cover near or around the river and potential evapotranspiration rates, which need to be further explored (Rice and Emanuel, 2017). Additionally, decadal scale oceanic processes such as the Pacific Decadal Oscillation (PDO) likely modulate the relationships between ENSO and streamflow. For example, warm PDO phases are generally associated with warm and dry conditions broadly across Central America (Mantua and Hare, 2002). However, the short reconstruction developed here did not allow us to thoroughly examine these potential multi-decadal features of climate variability in the region.

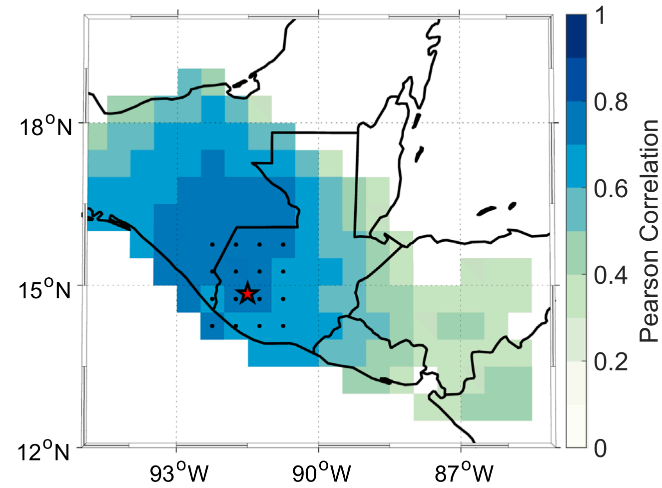

Fig. 5. August El Tunel discharge vs August CRU Ts4.01 precipitation 1979–2015 (only $p < 0.05$ correlations are shown).

An assessment of instrumental discharge compared to reanalysis data (ERA 5) for the common period (1981–2015), suggests a strong Pearson correlation between the series (Fig. 6). As expected, the instrumental discharge series measured at the outlet of the Upper Samalá River basin is associated with the precipitation regimes of the northern highlands of Guatemala that experience around 900 mm/year (see climatic regions of Guatemala in INSIVUMEH 2018). The record shows no association with the more extreme precipitation regimes of the "Boca Costa", which averages 4000 mm/year. This region lies just south of the study site (highlighted with a star in Fig. 6.

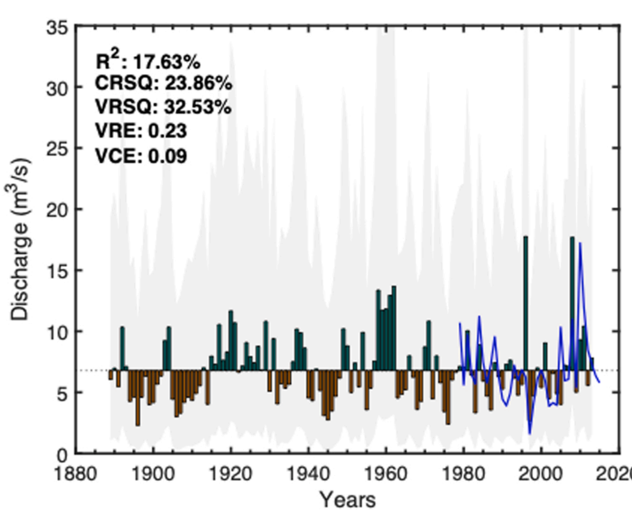

Fig. 4. Our final reconstruction explained ~17.63 % for the variance in the instrumental discharge data between 1979 and 2013. The final VRE and VCE values of our reconstruction model were 0.23 and 0.09 respectively. The confidence interval is shown in light gray shaded areas. The blue line represents the instrumental discharge. Years of above historical average discharge are shown in green bars. and years of below historical average discharge are shown in brown bars.

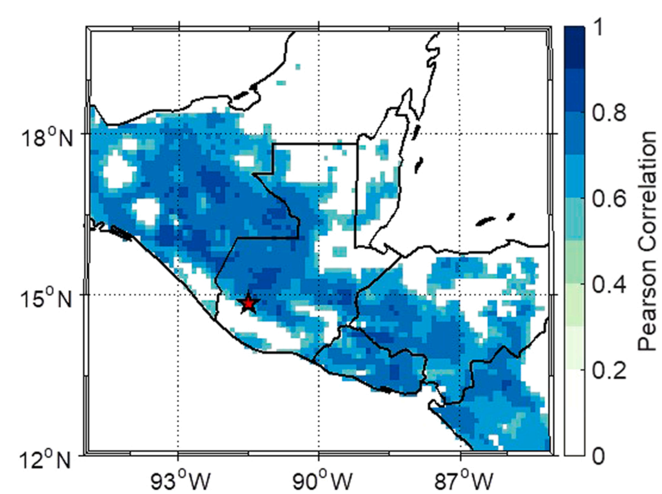

Fig. 6. August El Tunel discharge vs August ERA5 discharge 1981–2015 (only $p < 0.05$ correlations are shown).

4. Conclusions

Although our results suggest a rather modest explained variance for the historical discharge of the Samalá River, it supports other studies on the historical influence of ENSO on the hydrology of the Guatemalan highlands (Anchukaitis et al., 2013 and 2014, Anderson et al., 2018). This collection of knowledge based on tree-ring research is critical in understanding the potential impacts of global climate change to this region and could inform water resource management in the area (Hidalgo et al., 2013). For instance, if the association between ENSO and streamflow remains, the impact of increased evapotranspiration via warmer temperature changes in the Samalá Basin could affect the available runoff during the *dryer* ENSO years (Imbach et al., 2012). Similarly, beginning to understand the magnitude of the ENSO-streamflow relationship at a regional and local scale has the potential to inform seasonal forecasts on streamflow, which in turn can be used for water allocation to the different uses of the Samalá River streamflow (Chiew and Mcmahon, 2002).

Future tree ring studies on tropical streamflow reconstructions could incorporate the new reanalysis data and explore other proxies like early wood, late wood, and wood density, wood anatomy and wood isotopic composition as predictors of discharge (Starheim et al., 2013). Additionally, as more tree ring data becomes available in the region, future studies can harness the benefits of a multi-site and multi-species regional tree-ring to explore common climatic signals within a Basin to develop more skillful reconstructions. An improved tree-ring network will also allow for the examination of emerging questions such as the changing timing and intensity of the mid-summer drought across the latitudinal gradient in Central America (Anderson et al., 2019) and the influence of climatic drivers such as the North Atlantic Subtropical High (NASH) on drought variability in the region (Herrera et al., 2020; Bishop et al., 2019).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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