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Upper Nile River flow reconstructed to A.D. 1784 from tree-rings for a long-term perspective on hydrologic-extremes and effective water resource management

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ABSTRACT

The Nile River is one of the principal rivers in Africa, with Blue Nile (BNRiF) and Tekeze-Atbara (TARiF) rivers being its largest tributaries. However, long-term hydrological information is lacking in the Nile basin, which is a shortcoming to design and implement sustainable water management. We reconstructed river discharge since A.D. 1784 using tree-ring proxy data to (1) extend the short existing discharge records (2) examine long-term flow variability, and (3) identify characteristics of high- and low-flow periods and their connection with large-scale climate forcing factors like the El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole Mode (IOD). The chronology (RPC#1) correlates significantly with annual BNRiF ($r = 0.62$, $p < 0.001$) and TARiF ($r = .66$, $p < .001$) discharge. Reconstructed river discharge showed significant high-frequency variations at 2- to 4-year cycles, and sub-decadal and decadal periodicities at 7–10 and 10–14 years, respectively. The inter-annual discharge deviations from the mean during pluvial (dry) periods reached up to 38% (−32%) in BNRiF and 76% (−65%) in TARiF. El Niño and La Niña events matched with 40% and 59% of extreme-dry and extreme-pluvial episodes, indicating teleconnections influencing the regional rainfall and hydrological system. Reconstructed river discharge showed significantly positive spatial relationships with rainfall and negative spatial correlations with temperature across northern Ethiopia and large parts of the Sahel belt and the White Nile swamps in South Sudan. The short instrumental period did not adequately represent the full range of annual to multidecadal discharge variability present in the reconstruction. Hence, the data presented are crucial to extend hydrological records and to revise existing worst-case scenarios and water management strategies developed based on short instrumental records for water supply and energy production across the Nile basin.

1. Introduction

Water resources are strongly affected by climate change and are part of the globalization process (Hoff, 2009). However, the spatial and temporal distribution of global freshwater resources are uneven, thus a large proportion of the world's population is currently experiencing water shortage (Bigas, 2012; Degefu et al., 2018). Moreover, large-scale impacts of global climate change and anthropogenic greenhouse gas emissions are altering atmospheric circulation systems and the distribution and magnitude of rainfall over a large area of the world (IPCC, 2007; Onyutha and Willems, 2015; Ramanathan and Feng, 2009). This, in turn, directly affects the water level of several transboundary rivers and lakes which are mostly the only sources of fresh water (IPCC, 2014). More importantly, future adequacy of freshwater resources is difficult to assess, owing to a complex and rapidly changing geography of water demand and supply across the globe (Cosgrove and Loucks, 2015; Vorosmarty et al., 2000). Thus, water-related issues are of critical interest for many countries, particularly in the regions which

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experience frequent hydrological and meteorological droughts and are occupied by some of the poorest and least resilient communities (De Stefano et al., 2010; IPCC, 2014).

The hydro-geographic conditions of Africa are characterized by exceedingly uneven water resource distribution concentrated in a few large river basins shared by two or more countries (Freitas, 2013; Nash et al., 2016). Nile River is the chief river in Africa and the longest river in the world, extending from 4°S to 32°N. Its catchment covers about 10.3% of the total surface area of Africa and comprises a number of sub-basins with very different physical, topographic, hydrologic, and climatic characteristics (Sutcliffe and Parks, 1999). The Nile River receives its water from a network of various hydraulic systems, draining eleven-riparian countries (http://atlas.nilebasin.org/start/). However, up to 85% of total Nile flow is contributed by the Ethiopian highlands through the Blue Nile and Tekeze-Atbara rivers. The flow is seasonal, concentrated between June and September (Conway, 2000; Fielding et al., 2017; Freitas, 2013; Sutcliffe and Parks, 1999). The Nile River basin is highly prone to hydrological and meteorological drought (Oestigaard, 2012; Taye et al., 2011). Coupled with the rapidly growing regional population it may possibly intensify water-related transboundary challenges in the future (Nash et al., 2016; Oestigaard, 2012; Rahman, 2012). In addition, the climate and hydrological systems of the Nile basin are strongly influenced by remote weather forcing mechanisms, such as the El Niño–Southern Oscillation (ENSO), and the Indian Ocean dipole mode (IOD) of Sea surface temperatures, but their impact is complex and multidirectional (Conway, 2000; Diro et al., 2011; Nicholson, 2014). Rainfall tends to be high during La-Niña events and low during El-Niño events over the northern parts of the basin during summer and in the equatorial rainfall region during the March–May rainy season. On the contrary, across the equatorial and southern parts of Eastern Africa, La Niña/negative-IOD and El-Niño/positive-IOD-events are associated with below and above average rainfall during the October–November rainy season, respectively (Abtew et al., 2009; Camberlin et al., 2001; Nicholson and Kim, 1997; Siam and Eltahir, 2015; Tierney et al., 2013; Zaroug et al., 2014).

There are complex factors contributing to the challenges in predicting the Nile basin's hydrological and climate characteristic (Rahman, 2012; Swain, 2011). On top of this, instrumentally recorded rainfall and river flow data are often scarce, discontinuous and/or too short to reveal the natural variability within the hydrologic system and the impacts of climate change (Arnell and Lloyd-Hughes, 2014; Di Baldassarre et al., 2011; Nash et al., 2016). Thus, it is urgent to explore new data sources to resolve water-related conflicts and ensure sustainable utilization of trans-boundary water resources based on improving ecohydrological knowledge (IPCC, 2007; WWAP, 2015). In this context, proxy data that can archive absolute dating with a high temporal resolution have special relevance for this data-poor region. Tree rings are one of the most useful and readily available proxy data sources of this type (Fritts, 1976; Fritts et al., 1980). Dendrochronology is a well-established method for reconstructing rainfall and river flow records, especially in water-limited growing environments, where both tree-growth and river discharge respond positively to precipitation (Gebrekirstos et al., 2014; Mokria et al., 2017; Therrell et al., 2006). Tree-ring parameters like ring width and variations of stable isotopes of carbon and oxygen ($\delta^{13}C$ and $\delta^{16}O$) have emerged as an important source of evidence for paleohydrological and paleoclimate studies (Ballesteros-Cánovas et al., 2015; McCarroll et al., 2009). Tree-ring and $\delta^{13}C$ based long-term river flow reconstructions were reported from different countries, including Australia (Allen et al., 2015), Canada (Axelson et al., 2009), China (Liu et al., 2010), Ethiopia (Wils et al., 2010), India (Singh and Yadav, 2013), Indonesia (D'Arrigo et al., 2011), Russia (Agafonov et al., 2016), Turkey (Akkemik et al., 2007), and the USA (Allen et al., 2013). Besides reconstruction of discharge variability, such information is being used to develop hydrological scenarios to improve hydropower and water supply management strategies (Axelson et al., 2009; Rice et al., 2009; Stockton et al., 1976). Thus, tree-ring reconstructed hydrological information is the most economic and reliable available option to improve the spatiotemporal coverage of streamflow information and to better understand the long-term variability and the nature of extreme hydroclimate events across the Nile basin countries, where water resources management is becoming an increasingly complex issue. This study reconstructed the Blue Nile and Tekeze-Atbara river discharges using a combination of tree-ring width and carbon isotope proxy-data, to (1) extend the existing instrumental discharge records; (2) examine the long-term flow variability, and (3) characterize extreme hydrological-events and their connection with El Niño–Southern Oscillation (ENSO) and the Indian Ocean dipole mode (IOD) of sea surface temperatures.

2. Material and methods

2.1. Study area, river basin, and climate characteristics

This study was conducted in the Blue Nile and Tekeze-Atbara River basins, Northern Ethiopia (Fig. 1). These river basins encompass areas with high altitudinal variation, i.e., the eastern part of the basin has the highest elevation reaching 4600 m.a. s. l. descending gradually towards the western periphery of the basin where the elevation drops to approximately 500 m.a.s.l. (Fig. 1). The Blue Nile and Tekeze-Atbara rivers are the main components of the water-supply network to the main Nile River. On average, they contribute 48 and 11 billion m^3 water per year (Noaman and Quosy, 2017). We selected these rivers for their strategic importance for water supply in Ethiopia, Sudan, and Egypt. The Blue Nile river radiates from south of Lake Tana (Ethiopia) and drains into the Mediterranean Sea. Tekeze-Atbara River also rises from the Ethiopian highlands north of Lake Tana and stretches along the Eritrean border (Fig. 1).

The general climate characteristics of the study river basins are semi-arid in the northeast and humid in the southwest headwater source areas (Conway, 2000; Gebremicael et al., 2017; Melesse, 2011; Sutcliffe and Parks, 1999). Rainfall in the Blue Nile basin ranges from about 800 mm $year^{-1}$ near the Sudanese border to about 1400–1800 mm $year^{-1}$ near Lake Tana, and above 2000 mm $year^{-1}$ in the southwest within the "Didessa" basin (Conwazy, 2000; Melesse, 2011). The rainfall distribution over the Tekeze-Atbara river basin ranges from 400 mm $year^{-1}$ near Eritrea to more than 1000 mm $year^{-1}$ near Lake Tana (Gebremicael et al., 2017). Across the basins, the main rainy season occurs from June to September (JJAS), with the peak monthly rainfall occurring in July and August (Conway, 2000). Although the summer months (JJAS) account for a large proportion of mean annual rainfall in the study river basins, the proportion generally increases with latitude, ranging from 60% in the southwest to 80% at the north of Lake Tana (Conway, 2000). Blue Nile River is influenced by JJAS rainfall in the northern parts of the catchment and receives additional rainfall during the short rainy season (March–May, usually May is a dry month) across the southwest parts of the basin. In contrast, only a single wet season (JJAS) rainfall determines the volume and annual variability of Tekeze-Atbara River flow (Conway et al., 2004; Gebremicael et al., 2017). To this line, the magnitude and temporal pattern of the river flow typically follows that of rainfall seasonality (Conway et al., 2004; Gebremicael et al., 2017).

Generally, the variation in rainfall over the upper Blue Nile and Tekeze-Atbara river basins is a product of the seasonal excursion of