

Research Article

Hydroclimate Variability at Lake Tana, Ethiopia, Over the Past 6,000 Years: A Critical Synthesis of Geochemical and Isotopic Records

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Abstract

Lake Tana, the source of the Blue Nile in the northwestern Ethiopian highlands, is a climatically sensitive archive at the northern margin of the Intertropical Convergence Zone (ITCZ). Its sediments record changes in the balance between Atlantic/Congo Basin moisture and Indian Ocean/Red Sea moisture, making it a key site for understanding Afro-Asian monsoon dynamics. This review critically synthesizes geochemical (XRF element ratios: Zr/Rb, Ca/Ti, Rb/K) and isotopic (leaf-wax δD) records from Lake Tana to reconstruct hydroclimate variability over the past 6,000 years, evaluate proxy reliability, and identify research gaps. Available evidence indicates that the African Humid Period (AHP) terminated at Lake Tana by approximately 8,000 cal BP, significantly earlier than in the Sahara and North Africa (~5,000 cal BP), δD_{wax} records indicate that this transition was driven by eastward migration of the Congo Air Boundary (CAB), not solely by ITCZ southward retreat. Late Holocene aridification culminated in a pronounced low-stand at ~4,200 cal BP, coeval with the Egyptian Old Kingdom collapse. Existing XRF data (366–150,190 yr) provide a foundation but lack the sampling density needed to resolve centennial-scale variability in the past 6,000 years, and no dedicated high-resolution study exists for the past 2,000 years, a period encompassing the Aksumite civilization and the Little Ice Age. A dedicated high-resolution geochemical and isotopic study is urgently needed to address outstanding questions about natural variability versus anthropogenic impact, and to provide a longer historical context for water resource management in the Blue Nile basin under future global warming.

Keywords

Lake Tana, African Humid Period, Congo Air Boundary, XRF Geochemistry, Leaf-wax δD , Blue Nile

1. Introduction

1.1. The Strategic Importance of the Blue Nile and Lake Tana

Lake Tana is the largest lake in Ethiopia, covering approximately 3,000–3,200 km² at an elevation of about 1,788–1,830

m on a basaltic plateau near 12°N, 37°15'E [29]. Although roughly 2,000 km shorter than the White Nile, the Blue Nile, fed primarily by summer precipitation over the Ethiopian highlands, contributes approximately 54–60% of total downstream Nile discharge (rising substantially during peak sum-

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mer flow) and transports the large majority of the river's sediment load [25, 34]. Consequently, the hydroclimatic state of the Lake Tana basin is critical not only for regional ecology but also for sustaining the agricultural economies and livelihoods of millions of people in Sudan and Egypt.

Lake Tana lies near the northern margin of the Intertropical Convergence Zone (ITCZ). Even modest weakening of the summer monsoon can produce precipitation failure, helping explain the region's long history of droughts and famines. Understanding natural precipitation variability over the past several millennia is therefore essential for validating climate prediction models and assessing water-resource risks under future global warming. The Rain6K project addresses this need by using the varied sedimentary sequence of Lake Babogaya to reconstruct decadal-scale precipitation variability in central Ethiopia over the past 6,000 years, with the aim of clarifying the “source–sink” relationship between precipitation in the Blue Nile source region and downstream Nile flood records.

1.2. Climatic Setting

The climate of the Lake Tana region is controlled by the seasonal migration of the ITCZ and positional changes of the Congo Air Boundary (CAB). The CAB is a convergence zone over central Africa that separates Atlantic/Congo Basin air masses from Indian Ocean air masses. Under modern conditions, precipitation over the Ethiopian highlands is derived from both Atlantic/Congo Basin sources to the west and Indian Ocean sources to the east, with their relative contributions varying according to the east–west migration of the CAB [19, 30]. This mechanism is critical for interpreting paleoclimate records because the moisture sources have distinctly different isotopic compositions: Atlantic-derived (Congo Basin) moisture tends to be more depleted in δD , whereas Indian

Ocean-derived moisture is relatively enriched [7, 19].

1.3. Scientific Significance of the 6,000-Year Window

The past 6,000 years encompass the termination of the African Humid Period, the global-scale drought event at approximately 4.2 ka, the Medieval Warm Period, and the Little Ice Age, key climatic transitions. This interval also coincides with intensified human activity in the Nile Valley; Nilometer records of Nile water levels provide unique documentary evidence of climate–society relationships over the past ~2,000 years. High-resolution paleoclimate reconstructions from this window are therefore significant both for understanding climate dynamics and for providing a historical framework of human vulnerability and adaptability to climate change [7].

2. Regional Setting and Modern Climate

2.1. Geographic and Geological Context

Lake Tana is situated on the basaltic plateau of northwest Ethiopia at approximately 12°N, 37°15'E, and 1,830 m altitude [18, 29]. The lake occupies a tectonic basin positioned at the junction of three grabens, with extensive Tertiary lavas and tuffs in the surrounding area derived from traps that erupted approximately 30 million years ago [18]. These volcanic rocks have weathered into a distinctive modern landscape of cones, plugs, sills, and dykes, with equivalent outcrops forming numerous small islands within the lake [18]. The basin is characterized by recent faulting and associated continuing subsidence, which has created accommodation space for a sedimentary sequence exceeding 50 m in thickness [18].

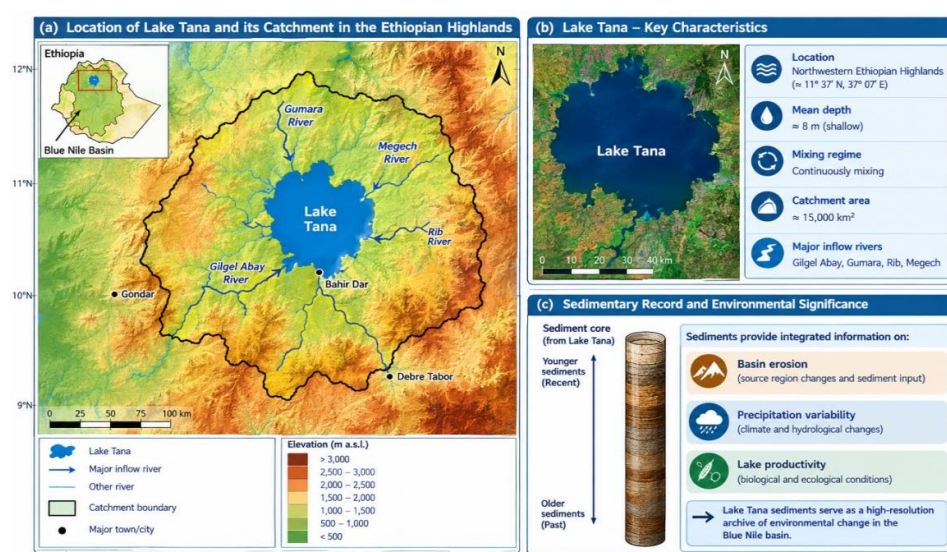


Figure 1. Location, catchment, key characteristics, and sedimentary significance of Lake Tana in the Ethiopian Highlands.

Figure 1. Location, catchment characteristics, major tributary inflows, shallow morphology, and sedimentary significance of Lake Tana for reconstructing environmental and hydrological changes in the Blue Nile Basin.

Figure 1(a) situates Lake Tana within the northwestern Ethiopian Highlands and delineates its approximately 15,000 km² catchment, emphasizing topographic connectivity between upland source areas and the lake. The four principal tributaries, Gilgel Abay, Gumara, Rib, and Megech, are represented as major pathways for water and sediment delivery, consistent with documented hydrological and sediment contributions [4]. Figure 1(b) highlights the lake's shallow morphology and continuously mixing character, features that influence sediment redistribution and ecological processes. Figure 1(c) conceptualizes the sedimentary archive, showing how accumulated deposits integrate signals of catchment erosion, hydrological variability, and lake productivity. Thus, Lake Tana sediments provide an important stratigraphic record for reconstructing environmental change in the Blue Nile Basin over time.

The lake is characteristically shallow, with reported mean depths ranging from 8 to 9 m and maximum depths of 14 to 14.8 m [15, 19]. With a drainage area of approximately 15,000 km², the Lake Tana basin constitutes about 20% of the lake surface itself [26]. The drainage network analysis reveals that the sub-basin is a seventh-order system with a dendritic drainage pattern and very fine drainage texture [26]. The four major tributaries; Gilgel Abay, Ribb, Gumera, and Megech, account for more than 80% of the total inflow, with the Gilgel Abay from the south, the Ribb and Gumera from the east, and the Megech from the north [26]. Morphometric analysis indicates that the Gilgel Abay, Ribb, and Gumera catchments are fifth-order streams, whereas the Megech catchment is a sixth-order stream [26]. The high bifurcation ratio values indicate substantial structural disturbance, the availability of erodible soils, and the occurrence of high overland flow and discharge [26].

High-resolution seismic reflection data from the northern part of Lake Tana reveal a previously unrecognized sedimentary sequence at least 50 m in depth [2]. The bases of alluvial fan structures overlying reflectors extend into the lake from the north shore, showing a shallow dip toward the shoreline, opposite to the normal disposition of fan sediments, suggesting that differential subsidence along the northern graben margin has created accommodation space for the deep sediment body [2]. Luminescence dating has generated a 250,000-year chronology for Lake Tana sediments, providing one of the longest independently dated lacustrine sediment records in eastern Africa [23]. This chronology agrees with independent radiocarbon dating in the upper part of the core and extends significantly beyond the range of radiocarbon dating [23].

2.2. Modern Climate and Hydrology

The climate of the Lake Tana basin is governed by the seasonal migration of the Intertropical Convergence Zone and associated monsoon dynamics [32]. Seasonal analysis reveals that the smallest amount of rainfall occurs in the Bega season, which is becoming drier with time, while the Belg and Kiremt

seasons are becoming wetter [32]. The Kiremt rainy season (June–September) accounts for approximately 78.1% of total annual rainfall in the basin, with Bega contributing about 9.4% and Belg approximately 12.5% [32]. The mean annual rainfall in the study area is 1,272 mm, of which 1,024 mm (80.5%) occurs during the summer rainfall season, with rainfall concentrated from June to September and greatest in July and August [32]. Analysis of rainfall trends from 1979 to 2015 indicates that Kiremt rainfall is increasing significantly at Debre Tabor station with a rate of 10.20 mm/year [32].

The hydrological regime of Lake Tana is tightly coupled to precipitation seasonality. The lake receives surface runoff from more than 40 tributary rivers, though more than 80% of the inflow is accounted for by the four major rivers [26]. Lake Tana has two major outlets: the Blue Nile River and the Tana-Beles tunnel hydropower outlet, which is controlled by gates [36]. Water level changes are directly caused by hydrological factors including rainfall, evaporation, runoff, infiltration, tributary inflow, discharge, and downward percolation of groundwater [36]. Teleconnections between Lake Tana water level changes and global sea surface temperatures have been documented, with significant correlations between water level rise during the rainy season and Pacific Ocean SST anomalies at lags of 0–1 month and 6–7 months [36]. A recurrent neural network model utilizing SST time series from the correlated western Pacific zone successfully simulated observed water level changes with a correlation coefficient of $r = 0.795$, demonstrating predictability at lead times of 6–7 months [36]. Correlation analysis of rainfall and SSTs indicates that rainfall in the Lake Tana basin is highly affected by variations of SSTs [32].

Recent decades have witnessed a dramatic acceleration in sediment delivery to Lake Tana. Comparison of bathymetric surveys conducted in 1940, 1987, 2006, and 2017 reveals that the lake's depth decreased by an average of 28 ± 11 cm over the past 77 years, equivalent to nearly 0.9 ± 0.4 Tg (million tons) of sediment [15]. Sediment deposition was 2.8 ± 2.3 mm a⁻¹ between 1940 and 1987, when agricultural intensification began, but nearly doubled to 5.0 ± 3.7 mm a⁻¹ after 1987 [15]. Spatially, sediment deposition is most significant in areas near the major river inlets, where 2 to 10 km long peninsulas have formed [15]. The increase in sediment deposition is primarily driven by newly formed valley bottom gullies formed after deforestation disturbed the hydrological equilibrium, and watershed outflow increased [15].

The implications of this sedimentation for the lake's sedimentary archive are significant. Bottom sediment samples collected from 60 locations reveal that the sediments have a median of 75% clay, 13% silt, and 9% sand, with clay greatest in the northwestern part and smallest in areas near the major rivers (Kebedew et al., 2020). The mean organic matter content of bottom sediment is 16 g kg⁻¹, total nitrogen is 0.8 g kg⁻¹, and Olsen available phosphorus is 19 mg kg⁻¹ [16]. Phosphorus concentrations peaked where water hyacinths were found

in the northeastern part of the lake [16]. The continuous resuspension of bottom sediments due to wave action at maximum lake depth means that the sedimentary record integrates both autochthonous and allochthonous inputs, complicating the isolation of specific environmental signals. These findings highlight the sensitivity of Lake Tana's hydroclimate to regional monsoon dynamics and global climate teleconnections, a consideration that must inform the interpretation of paleoclimate records extending over millennial timescales.

3. Methodological Framework: Geochemical and Isotopic Proxies

3.1. XRF Element Ratios

X-ray fluorescence (XRF) core scanning is a rapid, non-destructive, high-resolution method for acquiring sediment elemental composition, and has been widely applied in paleoclimate reconstruction from marine and lacustrine sedimentary sequences (Boyle, 2000). The XRF data generated by the PalaeoTana Project provide continuous records of element ratios such as Zr/Rb, Ca/Ti, and Rb/K, covering depths from 0.112 m to 62.686 m, corresponding to ages from 366 to 150,190 years [6]. These ratios serve as discriminants between terrigenous input and authigenic sedimentation, and their environmental interpretation requires synergistic multi-proxy analysis.

Table 1. Common XRF proxies in Lake Tana sediments and their environmental interpretations.

Proxy	Environmental Significance	Potential Influencing Factors
Zr/Rb	Zr enriched in coarse-grained silicates, Rb enriched in clay minerals; ratio tracks grain-size changes and erosion intensity	Provenance changes, grain-size effects
Ca/Ti	Ca represents authigenic carbonates, Ti represents terrigenous clastics; ratio tracks relative contributions of carbonate precipitation vs. terrigenous input	Dilution effects, diagenesis
Rb/K	Clay mineral composition; chemical weathering intensity	Multiple clay sources, K-feldspar interference

Table 1 summarizes three XRF element ratios employed as

environmental proxies in Lake Tana sediments. The Zr/Rb ratio tracks grain-size changes and erosion intensity, as Zr is enriched in coarse-grained silicates while Rb concentrates in clay minerals [5, 22]. The Ca/Ti ratio reflects the relative contributions of authigenic carbonate precipitation versus terrigenous clastic input, though dilution effects and diagenesis may complicate interpretation [5]. The Rb/K ratio indicates clay mineral composition and chemical weathering intensity, but multiple clay sources and K-feldspar interference require caution [5]. Critically, no single proxy provides unambiguous environmental signals; synergistic multi-proxy analysis is essential for robust paleoclimate reconstruction [22]. These proxies collectively enable identification of drought events at approximately 8.4, 7.5, and 4.2 cal kyr BP [22].

The interpretation of these proxies requires caution. Single element concentrations may be affected by dilution effects (e.g., changes in biological productivity) and redox processes [5]. Synergistic analysis of multiple proxies is a necessary condition for obtaining reliable environmental interpretations. [22] used magnetic and geochemical data from Lake Tana cores to identify multiple drought events over the past 17,000 years, including two pronounced arid phases at approximately 8.4 cal kyr BP and 7.5 cal kyr BP, as well as a drought event at approximately 4.2 cal kyr BP, the latter supporting an association between reduced Nile discharge and the collapse of the Egyptian Old Kingdom.

3.2. Leaf-Wax Hydrogen Isotopes (δD_{wax})

The hydrogen isotopic composition of leaf-wax n-alkanes (δD_{wax}) is an effective tool for reconstructing the isotopic composition of paleoprecipitation. The principle is based on: higher plants synthesize leaf waxes using environmental water, and δD_{wax} reflects the isotopic composition of source water (precipitation/soil water), superimposed with biosynthetic fractionation (ϵ_{app}) [20]. Apparent fractionation differs significantly among plant types: the mean ϵ_{wax-p} value is -107‰ for dicots and -140‰ for monocots [20]. Furthermore, the leaf-wax isotopic signal undergoes seasonal integration during deposition, potentially smoothing short-term climate variability [17].

[7] shows the reconstructed hydrological changes during the African Humid Period using leaf-wax δD from a 15,000-year sediment core from Lake Tana. δD_{wax} values range from -80‰ to -170‰ , primarily reflecting atmospheric precipitation processes rather than local evaporation effects. The record shows an abrupt shift from D-enriched to D-depleted values at approximately 13,000–11,500 years ago, indicating the full establishment of the African Humid Period; at approximately 8,500–8,000 years ago, δD_{wax} abruptly shifted back toward D-enriched values, marking the termination of the African Humid Period in this region [7].

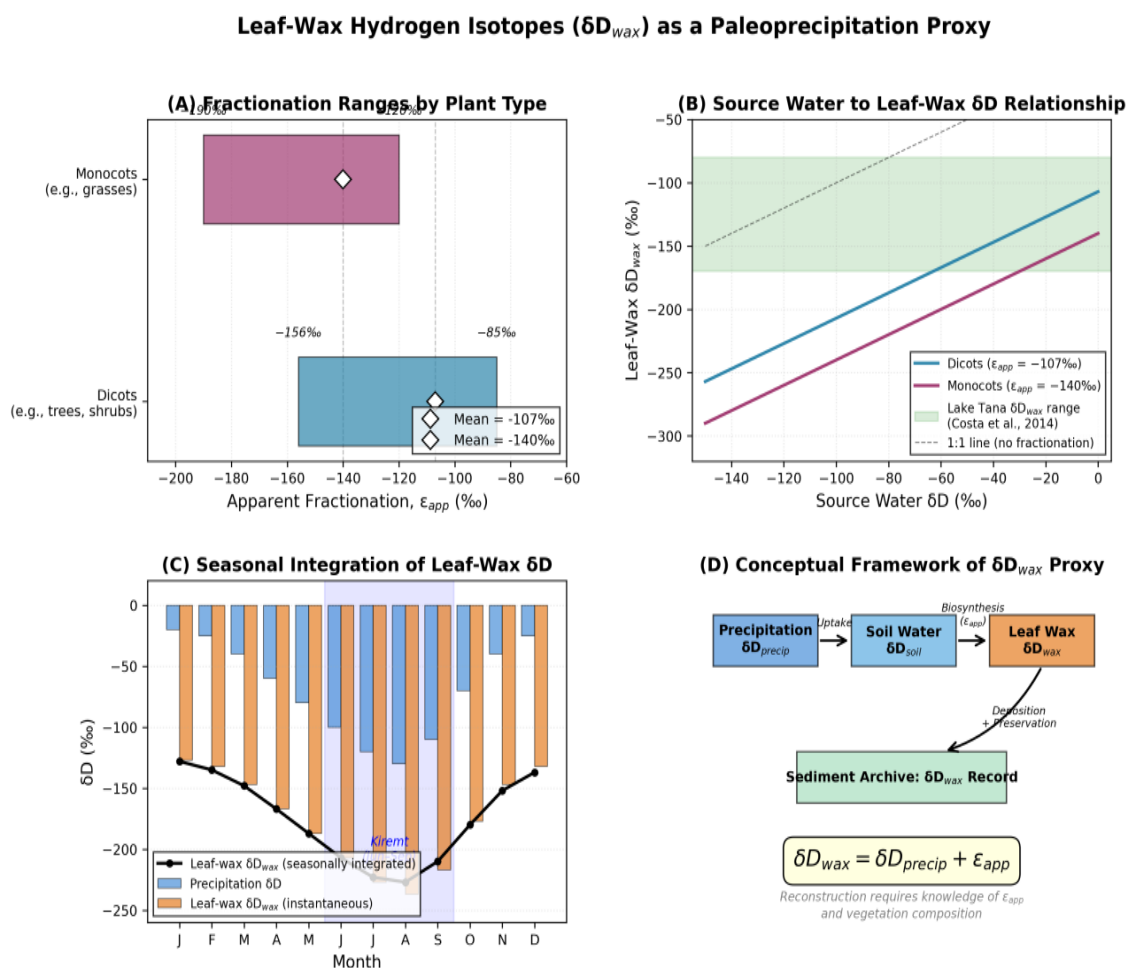


Figure 2. (a) Fractionation ranges by plant type. (b) Source water to leaf-wax δD relationship. (c) Seasonal integration effects. (d) Conceptual framework of the δD_{wax} paleoprecipitation proxy. Data from [7, 17, 20].

Figure 2(a) illustrates the apparent fractionation (ϵ_{app}) ranges for dicots ($-156‰$ to $-85‰$; mean = $-107‰$) and monocots ($-190‰$ to $-120‰$; mean = $-140‰$), following [20]. The non-overlapping means indicate that vegetation composition exerts a first-order control on δD_{wax} , introducing substantial uncertainty if unconstrained [20]. Figure 2(b) demonstrates the linear relationship between source water δD and leaf-wax δD_{wax} , with the shaded green band representing the Lake Tana δD_{wax} range of $-170‰$ to $-80‰$ reported by [7]. Critically, this range overlaps dicot and monocot trajectories, meaning that a single δD_{wax} value cannot uniquely resolve precipitation δD without independent vegetation information [20]. Figure 2(c) shows the seasonal integration effect, wherein the smoothed δD_{wax} signal (black line) substantially dampens the high-frequency precipitation variability (blue bars), particularly during the Kiremt monsoon. This smoothing, described by [17], biases leaf-wax records toward growing-season conditions and may obscure short-term extremes. Figure 2(d) presents the conceptual framework: $\delta D_{wax} = \delta D_{precip} + \epsilon_{app}$, emphasizing that reconstruction requires knowledge of both fractionation and vegetation composition

[7]. Collectively, these panels demonstrate that robust paleo-precipitation reconstruction demands multi-proxy vegetation constraints and careful consideration of seasonal integration biases [17, 20].

3.3. Chronological Framework

The chronology of the Lake Tana cores relies primarily on luminescence dating. [23] was generated an independent 250,000-year chronology that is consistent with radiocarbon ages in the upper section of the core and significantly extends beyond the radiocarbon dating limit, making it one of the longest independently dated lacustrine sediment records in eastern Africa. However, high-precision dating for the past 2,000 years still requires denser constraints using radiocarbon or short-lived isotopes (^{210}Pb , ^{137}Cs) [23]. The Rain6K project utilizes the varved sedimentary sequence of Lake Babogaya to provide an independent chronological framework for the past 6,000 years, which can be cross-validated with the Lake Tana record [10].

4. Hydroclimatic Evolution over the Past 6,000 Years

4.1. Termination of the African Humid Period (Approximately 8,000 Years ago)

Figure 3 presents a multi-panel comparison of the Lake Tana δD_{wax} record with three regional paleoclimate archives, illustrating the spatial heterogeneity of African Humid Period (AHP) termination across North and East Africa.

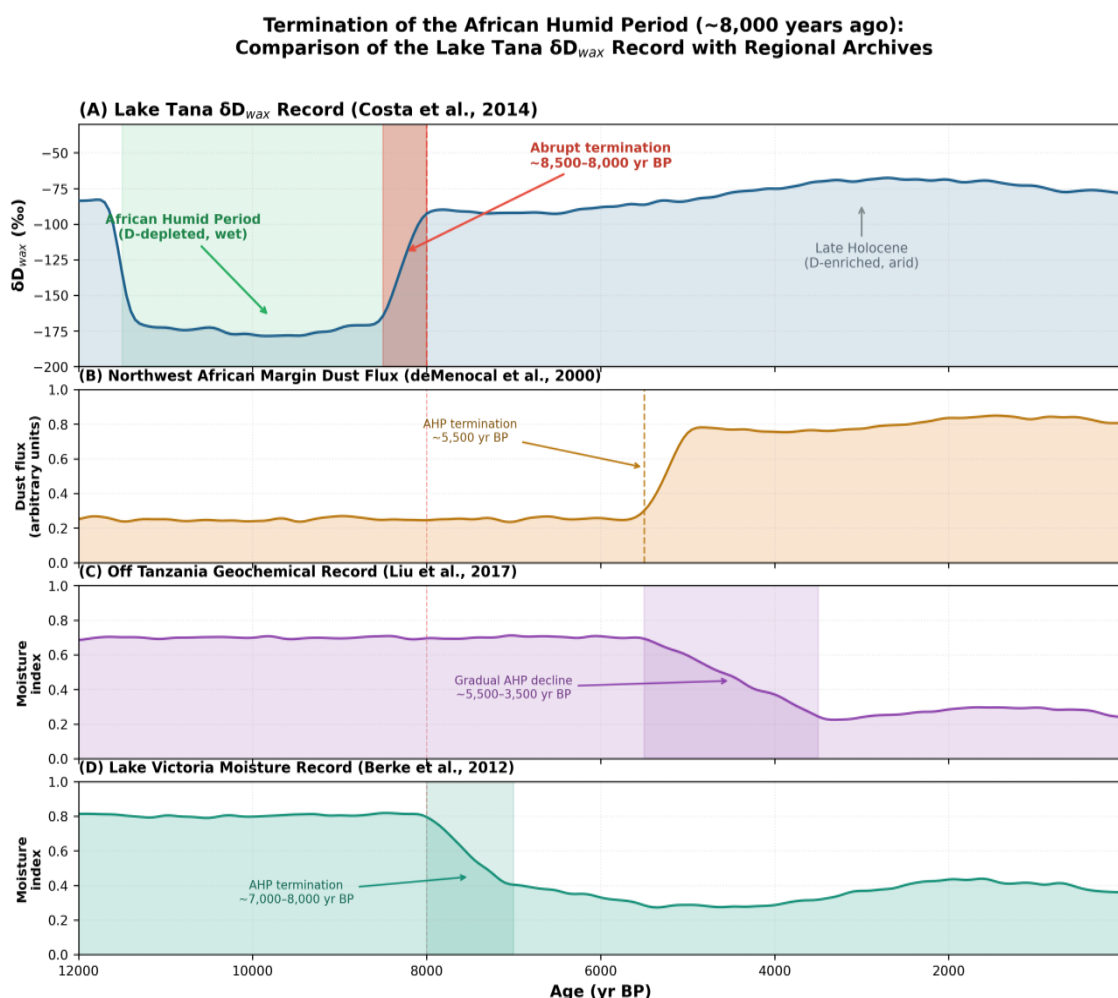


Figure 3. Comparison of Lake Tana δD_{wax} (a), Northwest African dust flux (b), off-Tanzania geochemical record (c), and Lake Victoria moisture (d) showing diachronous African Humid Period termination. Data from [3, 7, 8, 21].

Figure 3(a) shows the Lake Tana δD_{wax} record from Costa et al. (2014), which exhibits a pronounced shift from D-depleted values (-170‰) during the AHP to D-enriched values (-80‰) at approximately 8,500–8,000 yr BP, marking the abrupt and premature termination of humid conditions in the Blue Nile source region. This early termination contrasts sharply with the Northwest African margin dust flux record in Figure 3(b), where [8] document a synchronous and abrupt increase in dust flux at approximately 5,500 yr BP, indicating that aridification in the Sahara occurred some 2,500–3,000 years later than at Lake Tana. Figure 3(c) displays the geochemical record off Tanzania from [21], which shows a gradual, stepwise decline in moisture beginning at approximately

5,500 yr BP and culminating by 3,500 yr BP, consistent with a two-phase AHP structure (AHP I: ~10–8 ka; AHP II: ~8–5.5 ka) driven by changing moisture sources. Figure 3(d) presents the Lake Victoria moisture record from [3], which indicates AHP termination between approximately 8,000 and 7,000 yr BP, intermediate between the Lake Tana and Tanzania timings. The red dashed vertical line at 8,000 yr BP across all panels facilitates direct cross-site comparison, highlighting that AHP termination was neither synchronous nor uniform across Africa. Collectively, these records demonstrate that the Congo Air Boundary (CAB) migration, rather than a simple northward ITCZ retreat, exerted a first-order control on East African hydroclimate, with Lake Tana responding earliest due

to its sensitive position at the northern margin of the CAB influence zone [7, 13, 21].

The δD_{wax} record from Lake Tana reveals a significant regional phenomenon: the termination of the African Humid Period (AHP) in this region occurred markedly earlier than in most of North Africa. δD_{wax} underwent an abrupt shift from D-depleted (-170‰) to D-enriched (-80‰) values at approx-

imately 8,500–8,000 years ago, marking the substantive termination of the AHP in this region [7]. In contrast, marine sedimentary records from the northwestern African margin indicate abrupt AHP termination at approximately 5,500 years ago [8], while records from the Tanzania margin show a gradual termination beginning around 5,500 years ago and concluding by 3,500 years ago [21].

Congo Air Boundary (CAB) Migration and Moisture Source Changes at Lake Tana

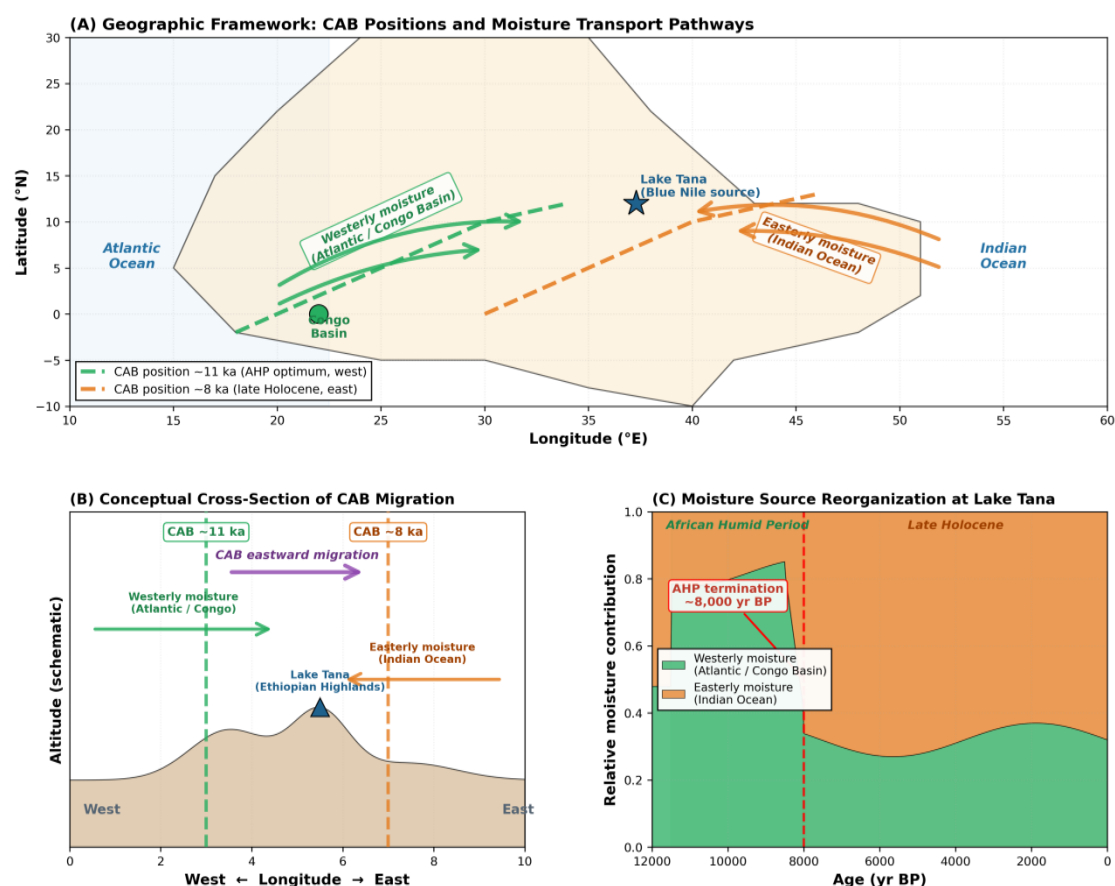


Figure 4. Conceptual model of Congo Air Boundary migration and moisture source changes at Lake Tana: (a) geographic framework; (b) cross-section; (c) moisture contributions. Modified from [7, 13, 21].

Figure 4 presents a conceptual model of Congo Air Boundary (CAB) migration and its control on moisture sources at Lake Tana over the past ~12,000 years. Figure 4(a) illustrates the geographic framework, showing two end-member CAB positions: a western position during the African Humid Period (AHP) optimum (~11 ka), when westerly moisture from the Atlantic and Congo Basin dominated precipitation at Lake Tana, and an eastern position during the late Holocene (~8 ka), when easterly Indian Ocean moisture became increasingly important [7]. Figure 4(b) shows a schematic west–east cross-section, with the Ethiopian Highlands acting as a topographic barrier; the eastward migration of the CAB (purple arrow) marks a fundamental reorganization of regional atmospheric

circulation [13]. Figure 4(c) quantifies this reorganization using a stacked area plot: westerly moisture contribution declined from approximately 82% during the AHP peak to approximately 32% in the late Holocene, with an abrupt transition at ~8,000 yr BP [7]. This shift coincides with AHP termination at Lake Tana, supporting the interpretation that CAB migration rather than simple ITCZ retreat was the primary driver of hydroclimatic change in the Blue Nile source region [21]. The model has critical implications for predicting future water availability in the Nile basin under continued warming.

Researchers attribute this temporal discrepancy to the reorganization of moisture sources rather than simple precipitation reduction [7]. During the AHP optimum (approximately

11,000 years ago), Lake Tana precipitation was primarily derived from westerly sources, the Congo Basin and tropical Atlantic, characterized by more depleted δD values (Costa et al., 2014). By approximately 8,000 years ago, as the Congo Air Boundary (CAB) shifted eastward, westerly moisture transport decreased, and the proportion of D-enriched moisture from the eastern Indian Ocean increased [7]. This mechanism indicates that East African climate is not controlled solely by a single atmospheric circulation pattern involving northward ITCZ migration; the east-west migration of the CAB is equally critical [7, 13]. Marine sedimentary records

off Tanzania further support this interpretation: the AHP is divided into two humid phases, with AHP I (approximately 10–8 ka) dominated by Atlantic moisture transported westward via the CAB, and AHP II (approximately 8–5.5 ka) associated with additional moisture contributions from the western Indian Ocean [21]. A recent study suggests that the rapid termination of the AHP was triggered by northern high-latitude cooling, which weakened the Tropical Easterly Jet and reduced summer precipitation in the Sahel-Sahara region, tipping the hydrological system toward an arid state [28].

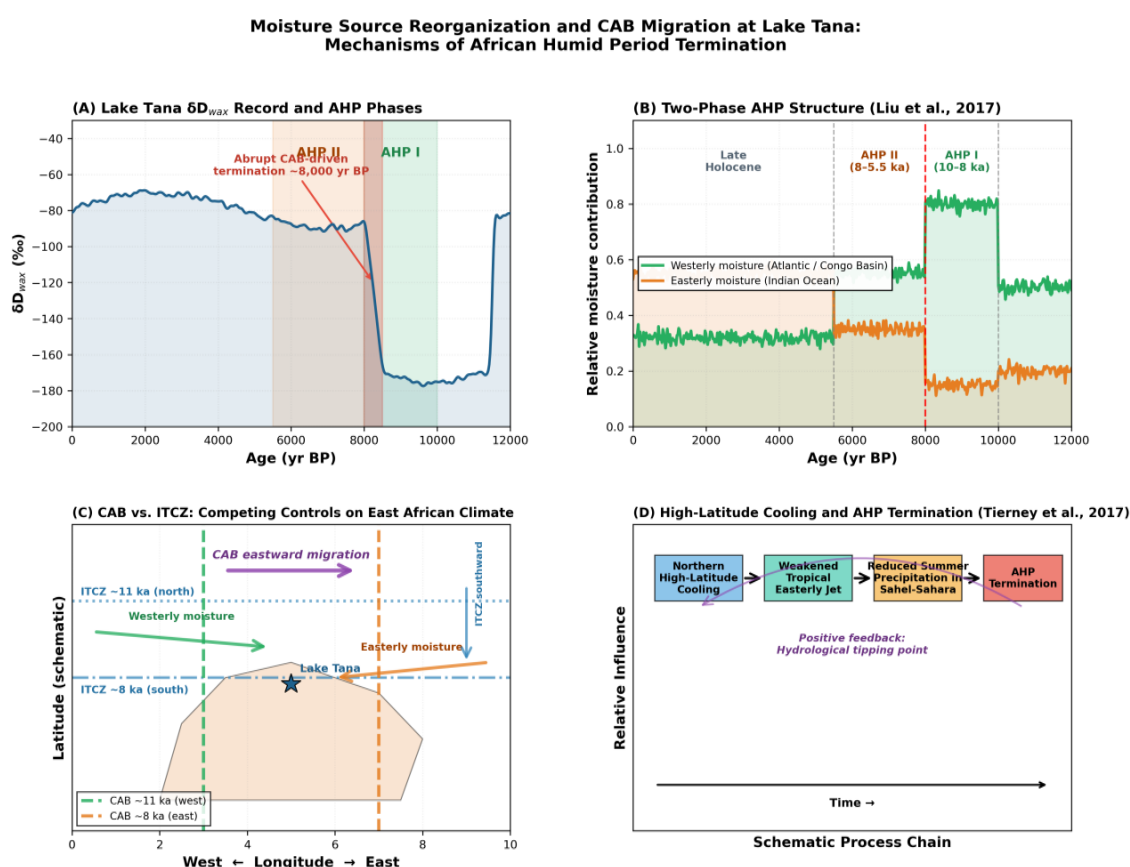


Figure 5. Moisture source reorganization and CAB migration at Lake Tana: (a) δD_{wax} record; (b) two-phase AHP structure; (c) CAB versus ITCZ controls; (d) high-latitude cooling mechanism. Modified from [7, 13, 21, 28].

Figure 5 presents the mechanisms driving moisture source reorganization and African Humid Period (AHP) termination at Lake Tana. Figure 5(a) shows the Lake Tana δD_{wax} record, with AHP I (10–8 ka) and AHP II (8–5.5 ka) phases highlighted, and the abrupt CAB-driven termination at ~8,000 yr BP marked in red [7]. Figure 5(b) quantifies the two-phase AHP structure described by [21]: AHP I was dominated by westerly Atlantic/Congo Basin moisture (~80%), while AHP II saw increased easterly Indian Ocean contributions (~35%), reflecting progressive CAB eastward migration. Figure 5(c) contrasts competing controls on East African climate: CAB

eastward migration versus ITCZ southward retreat, emphasizing that CAB migration exerted first-order control on Lake Tana hydroclimate [13]. Figure 5(d) illustrates the process chain proposed by [28]: northern high-latitude cooling weakened the Tropical Easterly Jet, reducing Sahel-Sahara precipitation and tipping the system toward aridity.

4.2. Late Holocene Aridification (Approximately 6,000–0. Years ago)

After approximately 8,000 years ago, the δD_{wax} record persistently maintains D-enriched values, indicating that the

late Holocene was dominated by relatively arid hydrological conditions overall [7]. This trend is consistent with the continued decline in Northern Hemisphere summer solar insolation (orbital-scale forcing): as precession parameters changed, Northern Hemisphere summer insolation decreased, the tropical rain belt retreated southward, and East African monsoon

precipitation weakened [8]. Records off Tanzania show that the AHP termination process began at approximately 5,500 years ago and was completed by approximately 3,500 years ago [21].

Table 2. Comparison of African Humid Period termination timing across East African sites.

Site	AHP Termination	Dominant Moisture Source	Reference
Lake Tana, Ethiopia	~8000 cal BP	Atlantic → Indian Ocean	[7]
Off Tanzania	~5500–3500 cal BP	Atlantic + Indian Ocean	[21]
Lake Victoria	~7000–8000 cal BP	Atlantic	[3]
Northwest African margin	~5500 cal BP	Atlantic	[8]

Table 2 compares African Humid Period (AHP) termination timing across four East and North African sites, revealing pronounced diachroneity. Lake Tana exhibits the earliest termination at ~8,000 cal BP, driven by a shift from Atlantic to Indian Ocean moisture via Congo Air Boundary (CAB) migration [7]. Lake Victoria terminates slightly later at ~7,000–8,000 cal BP under Atlantic influence [3]. Off Tanzania, termination is gradual (~5,500–3,500 cal BP) with mixed moisture sources [21], while the Northwest African margin terminates abruptly at ~5,500 cal BP [8]. This spatial gradient confirms that CAB migration, not ITCZ retreat alone, controlled East African hydroclimate.

Lake Victoria records indicate repeated short-lived arid intervals during the Holocene, including events at approximately 10.5, 9, 7.8–7.2, 4, and 3.2–3.0 cal ka BP [33]. These events suggest that the late Holocene was not uniformly arid but punctuated by century-scale drought episodes, which may have had significant ecological and societal consequences [33].

4.3. The 4,200-Year Event and the Collapse of the Egyptian Old Kingdom

At approximately 4,200 years ago, Nile discharge reached a pronounced minimum [22]. This paleoclimatic event (the 4.2 ka BP event) is clearly evidenced in archaeological, geoarchaeological, and bioarchaeological records from Egypt [37]. Studies indicate that this event led to aridification in Egypt, reduced Nile water levels, aeolian sand incursion into the Nile Valley, crop failure, and famine across ancient Egypt [3, 37]. As a compound event, it played an important role in the collapse of the Old Kingdom (approximately 2181 BCE), with impacts persisting into the First Intermediate Period [31]. The 4.2 ka event has been formally recognized as the chronological divider between the warmer middle Holocene and the

cooler late Holocene [31]. Research further indicates that climatic stress, including reduced Nile floods imposed significant hardship on ancient Egyptian society, but ancient society’s demonstrated remarkable resilience [37]. Urban expansion, construction of grain storage facilities, and livelihood diversification were key adaptive responses [37]. The Lake Tana XRF data cover this interval [6], but dedicated high-resolution studies specifically targeting the 4,200-year event are currently lacking, and precise dating and environmental reconstruction for this period require further work [22].

4.4. The Past 2,000. Years: Research Gap and Data Potential

Among the literature retrieved, no dedicated high-resolution geochemical study specifically targeting the past 2,000 years at Lake Tana has been identified. However, this period holds significant scientific value: it encompasses the rise and fall of the Aksumite civilization, agricultural expansion in the Ethiopian highlands, and the Little Ice Age [28]. Stable hydrogen isotope analysis of land-plant derived fatty acids from soil sequences in the Horn of Africa indicates that both D'MT (ca 2750–2350 cal y BP) and the Aksumite (ca 2100–1250 cal y BP) polities rose during wetter intervals of the drier part of the Holocene (after ca 6000 cal y BP) [28]. These results support hypotheses that the rise of civilizations was favored by specific climatic conditions, but patterns of land clearing differed during the declines of D'MT and the Aksumite [28].

Records from western Uganda indicate century-scale droughts centered on AD 0, ~1100, ~1550, and 1750 during the last 2000 years [24]. These results suggest regional variability of East African climate during the main phase of the Little Ice Age (AD ~1500 to 1800), with westernmost East Africa experiencing drought while areas farther east were wet [24].

The Rain6K project is currently reconstructing decadal-scale precipitation variability over the past 6,000 years using the varved sedimentary sequence of Lake Babogaya, and will compare results with ancient Egyptian Nilometer records to explore the relationship between source-region precipitation variability and downstream flood expression [10]. The existing 96 m core material from Lake Tana provides the material basis for densified sampling and dedicated geochemical analysis targeting the past 2,000 years [18].

Figure 6 presents the spatial and temporal patterns of late Holocene climate variability in East Africa alongside the Rain6K research framework. Figure 6(a) shows the western Uganda moisture record, which exhibits century-scale

droughts centered on AD 0, ~1100, ~1550, and ~1750, with the Little Ice Age (AD ~1500–1800) marked by pronounced drying [24]. Figure 6(b) illustrates the spatial contrast during the LIA: western Uganda crater lakes record dry conditions while Lake Victoria and areas farther east were wet, demonstrating a strong east–west moisture gradient across East Africa [24]. Figure 6(c) shows the Rain6K project framework, which is reconstructing decadal-scale precipitation variability over the past 6,000 years using varved sediments from Lake Babogaya and comparing results with Egyptian Nilometer records to explore source–sink relationships between Ethiopian precipitation and downstream Nile floods [10].

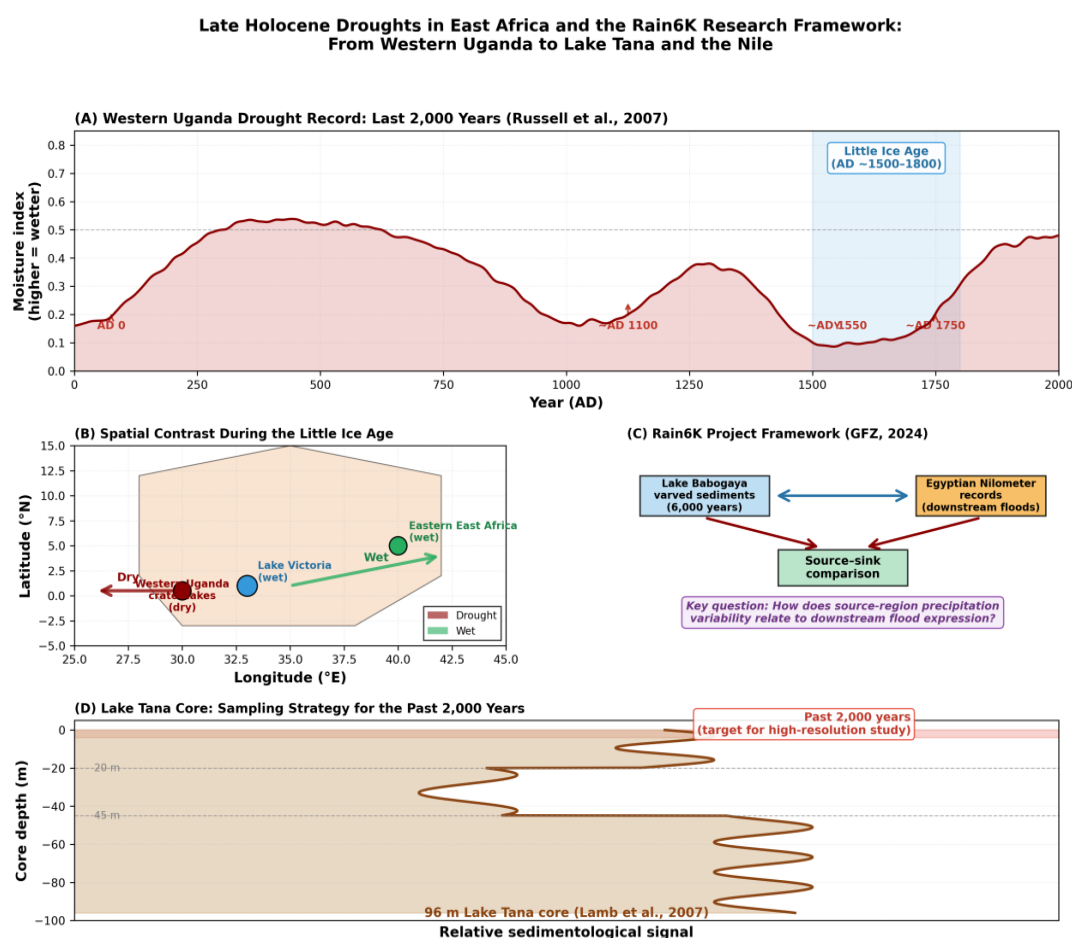


Figure 6. Late Holocene droughts in East Africa and the Rain6K framework: (a) western Uganda drought record; (b) LIA spatial contrast; (c) Rain6K project framework; (d) Lake Tana sampling strategy. Modified from [10, 18, 24].

Figure 6(d) depicts the 96 m Lake Tana core, with the top ~4 m identified as the target for high-resolution sampling and dedicated geochemical analysis of the past 2,000 years [18]. Together, these panels demonstrate that existing records provide a foundation for understanding regional climate dynamics, but a high-resolution Lake Tana study is essential to resolve decadal- to centennial-scale variability and distinguish climatic from anthropogenic signals [10, 18, 24].

5. Discussion

5.1. Moisture Source Dynamics: CAB vs. ITCZ

Synthesizing available evidence, the eastward migration of the Congo Air Boundary (CAB) emerges as the dominant factor controlling Lake Tana's hydroclimate over the past 8,000

years, while ITCZ positional changes play a secondary modulating role [7]. The δD_{wax} record exhibits D-depleted values (-170‰ to -100‰) from approximately 11.5 to 8.5 ka, followed by a pronounced shift to D-enriched values (-80‰) from ~ 8 ka to the present [7]. This transition reflects the reorganization of atmospheric moisture sources rather than a simple reduction in precipitation amount [1, 7]. During the African Humid Period (AHP) optimum, precipitation at Lake Tana was primarily derived from westerly sources, the Congo Basin and tropical Atlantic, which are characterized by more depleted δD values [7]. The CAB, defined as the convergence zone over Central Africa separating Atlantic and Indian Ocean

air masses, exerts a first-order control on the relative contribution of these moisture sources [13].

Magnetic and geochemical core data spanning the last 17,000 years provide complementary evidence for the timing and nature of hydroclimatic change at Lake Tana [22]. Lake Tana overflowed into the Blue Nile around 15.3 cal kyr BP, resulting in a loss of solutes and rapid freshening of lake water [22]. A subsequent period of lake lowering and reduced runoff occurred between 13.0 and 11.2 cal kyr BP, coincident with the Younger Dryas, causing formation of a desiccation surface [22]. The dramatic refilling of the lake following this lowstand, attributed to increased rainfall, led to downcutting into the desiccation surface and reworking of sediments [22].

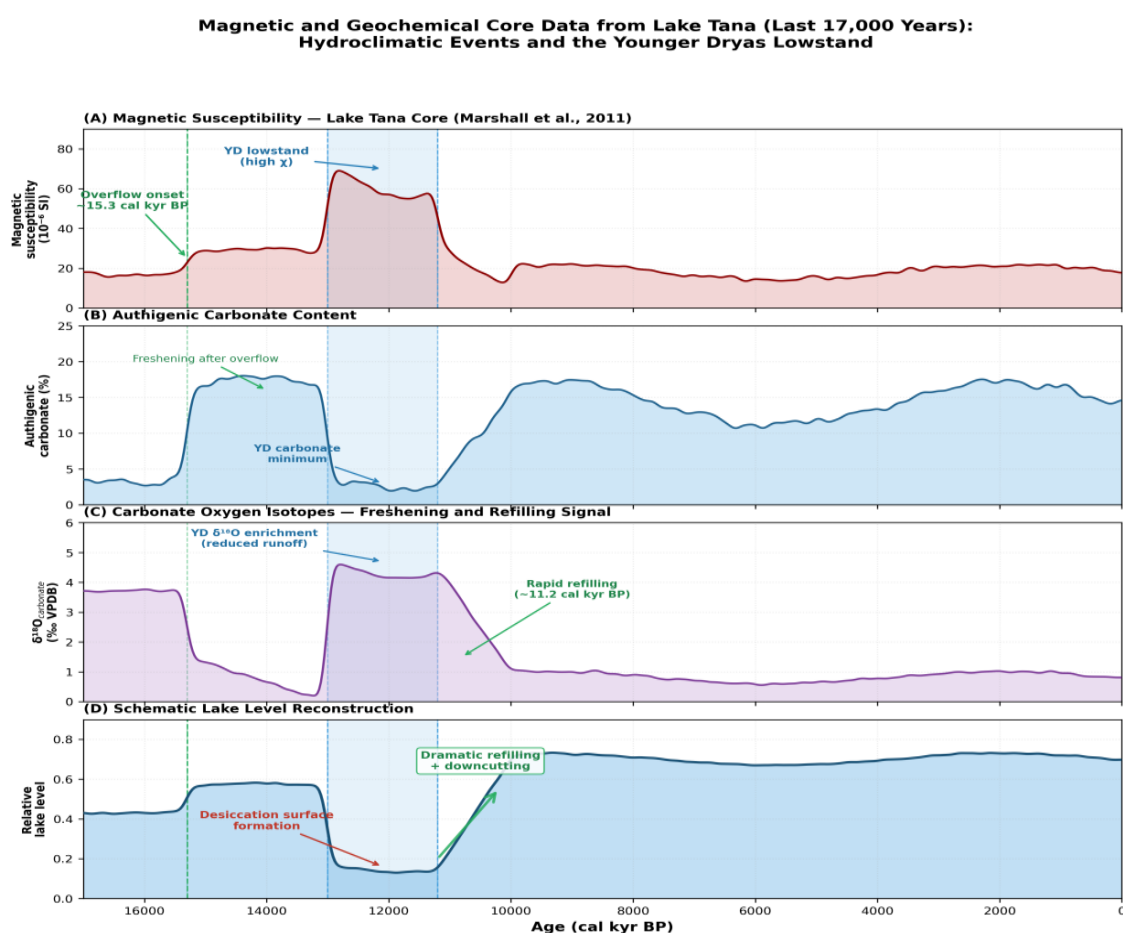


Figure 7. Magnetic and geochemical core data from Lake Tana (last 17,000 years): (a) magnetic susceptibility; (b) authigenic carbonate; (c) carbonate $\delta^{18}O$; (d) lake level reconstruction. Modified from [22].

Figure 7 present magnetic and geochemical core data from Lake Tana spanning the last 17,000 years, illustrating the sequence of hydroclimatic events described by [22]. Figure 7(a) shows magnetic susceptibility, which exhibits elevated values ($65\text{--}75 \times 10^{-6}$ SI) during the 13.0–11.2 cal kyr BP interval, consistent with increased detrital input and lake lowering during the Younger Dryas [22, 24]. Figure 7(b) displays authigenic carbonate content, which rises sharply after the ~ 15.3 cal kyr BP overflow, reflecting the loss of solutes and rapid

freshening of lake water [22]. Figure 7(c) presents carbonate $\delta^{18}O$, which shows enrichment during the Younger Dryas (4.5–5.0‰) due to reduced runoff and evaporative concentration, followed by rapid depletion after ~ 11.2 cal kyr BP as the lake refilled [22]. Figure 7(d) provides a schematic lake level reconstruction, showing desiccation surface formation at $\sim 13.0\text{--}11.2$ cal kyr BP and the dramatic refilling and downcutting that followed [22].

The spatial heterogeneity of AHP termination across East

Africa, ranging from approximately 8,000 cal BP at Lake Tana to 5,500–3,500 cal BP off Tanzania, likely reflects the differential influence of CAB position on moisture sources at different latitudes [7, 21]. At Lake Victoria, molecular records of δD and TEX86 indicate coherent hydroclimate and temperature changes, with an increase in warm, wet conditions peaking in the early Holocene before gradually cooling and drying to minimum values at approximately 4.7–3.2 ka [3]. This pattern is consistent with orbitally-forced tropical climate dynamics modulated by the relative contributions of Atlantic versus Indian Ocean moisture [3].

5.2. Linkages to Nile Discharge and Human History

Hydroclimatic variability at Lake Tana is intimately linked to downstream Nile flood records through Blue Nile discharge. The lake contains 50% of Ethiopia's freshwater resources and maintains hydrologic balance mainly through evaporation (64% of water loss) and outflow via the Blue Nile [18]. This hydrological connectivity means that changes in Lake Tana's water balance directly influence the discharge regime upon which downstream civilizations depended [18].

The drought event at approximately 4.2 ka BP constituted the regional climatic context for the collapse of the Egyptian Old Kingdom [37]. Comprehensive synthesis of archaeological, geoarchaeological, and bioarchaeological evidence demonstrates that this phase of severe global drought had critical environmental, economic, and political impacts in Ancient Egypt [37]. It led to aridification, a decline in the Nile level and Nile-fed lakes, encroachment of aeolian desert sand into the Nile Valley, lower crop yields, and famine across ancient Egypt [1, 37]. As a compound event, it played an important role in the collapse of the Old Kingdom (ca. 2181 BC), with effects continuing into the First Intermediate Period (ca. 2181–2055 BC) when Egypt witnessed political fragmentation [37].

The 4.2 ka BP event has been formally recognized as a significant global climate anomaly, with evidence attested in many regions worldwide (Weiss, 2017). At Lake Tana, the dry episode at approximately 4.2 cal kyr BP, identified through multiple proxy indicators, supports the view that reduced Nile flow was a contributing factor to the demise of the Egyptian Old Kingdom [22]. Nilometer records from the past 2,000

years provide a unique independent dataset for validating precipitation reconstructions in the Lake Tana source region, though this comparison has not yet been systematically undertaken [10]. The integration of paleoclimate reconstructions with historical Nile flood records would substantially strengthen understanding of source-to-sink hydroclimatic linkages [10].

5.3. Human Impact

In recent decades, human activities in the Lake Tana basin have significantly intensified sediment delivery, creating a superimposed anthropogenic signal on natural climate variability (Kebedew et al., 2021). Bathymetric surveys conducted in 1940, 1987, 2006, and 2017 reveal that the lake's depth decreased by an average of 28 ± 11 cm over 77 years, equivalent to nearly 0.9 ± 0.4 Tg of sediment [15, 27]. Sedimentation rates were 2.8 ± 2.3 mm a⁻¹ during 1940–1987, but nearly doubled to 5.0 ± 3.7 mm a⁻¹ after 1987 [15, 35]. This increase is primarily driven by newly formed valley bottom gullies formed after deforestation disturbed the hydrological equilibrium, and watershed outflow increased [9, 15].

Figure 8 presents contour maps visualizing the spatial patterns of human-induced sediment delivery in Lake Tana over the period 1940–2017, based on bathymetric surveys analyzed by [1, 15]. Figure 8(a) shows the modern bathymetry, with maximum depths (14–15 m) concentrated in the central-northern basin and shallower margins near river inlets. Figure 8(b) displays cumulative sediment thickness, revealing pronounced depositional maxima exceeding 0.28 m near the Gilgel Abay (south), Ribb (east), Gumara (northeast), and Megech (north) inlets, where sediment plumes have formed 2–10 km long peninsulas [15]. Figure 8(c) presents sedimentation rates derived from bathymetric change, with rates exceeding 4 mm a⁻¹ near major inlets, nearly double the basin-wide average of 2.8 ± 2.3 mm a⁻¹ during 1940–1987 [14, 15]. Figure 8(d) shows cumulative depth decrease, with a basin-wide mean of 28 ± 11 cm over 77 years, equivalent to nearly 0.9 ± 0.4 Tg of sediment [15]. The contourf approach effectively captures the spatial heterogeneity of sediment delivery, demonstrating that deposition is focused near deforested catchments where valley-bottom gullies have formed following hydrological disturbance. This anthropogenic signal is superimposed on natural climate variability, requiring careful differentiation between climatic and human-driven signals in recent sedimentary records [12, 15].

Human Impact on Sediment Delivery in the Lake Tana Basin: Contourf Maps of Bathymetric Change and Sedimentation (1940-2017)

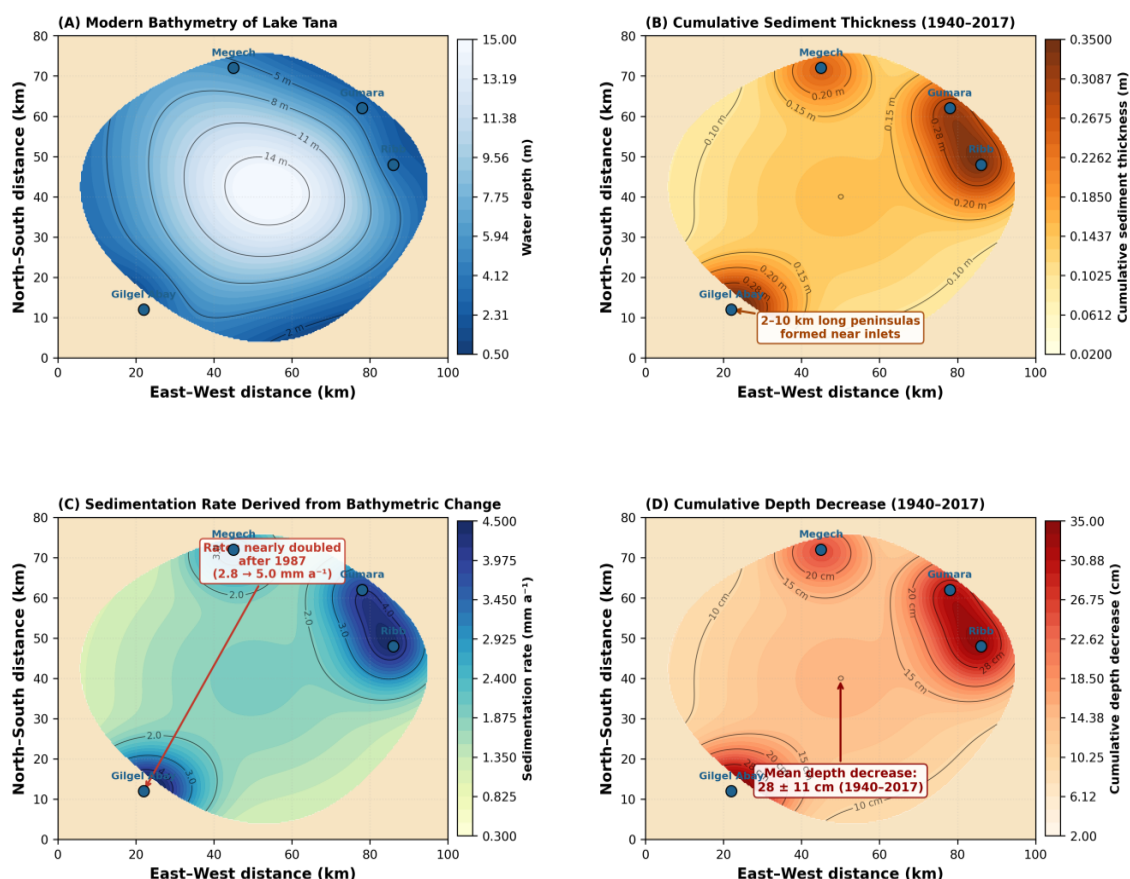


Figure 8. Contourf maps of human impact on sediment delivery in Lake Tana (1940–2017): (a) bathymetry; (b) sediment thickness; (c) sedimentation rate; (d) depth decrease. Modified from [15].

Spatially, sediment deposition was most significant in areas near the major river inlets, where 2 to 10 km long peninsulas were formed [15]. This pattern reflects the focused delivery of eroded material from deforested catchments to the lake margins [15]. The anthropogenic signal is superimposed on natural climate variability, requiring careful differentiation between climatic signals and human disturbance when interpreting recent sedimentary records [15]. The recent acceleration of sediment delivery also has implications for the interpretation of paleoclimate proxies in the uppermost sediment intervals, as changes in grain size and composition may reflect catchment disturbance rather than climatic forcing [11, 15].

6. Conclusions and Research Agenda

6.1. Main Conclusions

The hydroclimate of Lake Tana over the past 6,000 years is characterized by the premature termination of the African Hu-

mid Period (approximately 8,000 years ago), significantly earlier than in other parts of North Africa, reflecting moisture source reorganization driven by Congo Air Boundary (CAB) eastward migration. This early termination demonstrates that East African climate is not controlled solely by ITCZ migration, but equally by zonal moisture transport dynamics. The late Holocene is characterized by overall aridification, and the pronounced low-stand at approximately 4,200 years ago coincides with the regional climatic context of low Nile discharge and the collapse of the Egyptian Old Kingdom. Existing geochemical and isotopic data provide a robust framework, but high-resolution records for the past 2,000 years remain absent.

6.2. Research Agenda

Five priorities emerge. First, high-resolution XRF scanning should densify the past 2,000 years of the Lake Tana core to obtain decadal- to centennial-scale element ratio records (British Geological Survey, 2018). Second, multi-proxy integration combining δD_{wax} , GDGTs, pollen, and charcoal analysis

is needed to distinguish climatic from anthropogenic influences. Third, a high-precision chronology for the past 2,000 years should be established using ^{210}Pb , ^{137}Cs , and AMS ^{14}C . Fourth, paleoclimate reconstructions should be systematically compared with Nile Nilometer records and Aksumite archaeological records. Fifth, proxy records should be compared with PMIP transient simulations to assess the relative contributions of different forcing mechanisms.

Abbreviations

XRF	X-ray Fluorescence
CAB	Congo Air Boundary
ITCZ	Intertropical Convergence Zone

Author Contributions

Belay Sitotaw Goshu: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft

Conflicts of Interest

The author declares no conflicts of interest.

References

- [1] Alemayehu, M., et al. (2021). Sediment deposition (1940–2017) in a historically pristine lake in a rapidly developing tropical highland region in Ethiopia. *Earth Surface Processes and Landforms*, 46(8), 1589–1603.
- [2] Bates, C. R., Lamb, H. F., & Umer, M. (2007). High-resolution seismic investigation of Lake Tana, northern Ethiopia. *Near Surface Geophysics*, 5(4), 243–250. <https://doi.org/10.3997/1873-0604.2007006>
- [3] Berke, M. A., Johnson, T. C., Werne, J. P., Grice, K., Schouten, S., & Sinninghe Damsté, J. S. (2012). Molecular records of climate variability and vegetation response since the Late Pleistocene in the Lake Victoria basin, East Africa. *Quaternary Science Reviews*, 55, 59–74. <https://doi.org/10.1016/j.quascirev.2012.08.014>
- [4] Bogale, A. (2020). Review, impact of land use/cover change on soil erosion in the Lake Tana Basin, Upper Blue Nile, Ethiopia. *Applied Water Science*, 10, 235. <https://doi.org/10.1007/s13201-020-01325-w>
- [5] Boyle, J. F. (2000). Rapid elemental analysis of sediment samples by isotope source XRF. *Journal of Paleolimnology*, 23(2), 213–221. <https://doi.org/10.1023/A:1008185105395>
- [6] British Geological Survey. (2018). Lake Tana core XRF data (NERC grants NER/B/S/2002/00540 and NE/D012996/1) [Data set]. UK Gov Data. <https://www.data.gov.uk/dataset/7690bd01-9e50-440f-9185-90aac5945137/lake-tana-core-xrf-data-nerc-grants-ner-b-s-2002-00540-and-ne-d012996-1>
- [7] Costa, K., Russell, J., Konecky, B., & Lamb, H. (2014). Isotopic reconstruction of the African Humid Period and Congo Air Boundary migration at Lake Tana, Ethiopia. *Quaternary Science Reviews*, 83, 58–67. <https://doi.org/10.1016/j.quascirev.2013.10.031>
- [8] deMenocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L., & Yarusinsky, M. (2000). Abrupt onset and termination of the African Humid Period: Rapid climate responses to gradual insolation forcing. *Quaternary Science Reviews*, 19(1–5), 347–361. [https://doi.org/10.1016/S0277-3791\(99\)00081-5](https://doi.org/10.1016/S0277-3791(99)00081-5)
- [9] Gebregiorgis, D., et al. (2021). Application of XRF scanning to different geological archives. *Earth and Space Science*, 8(9), e01589.
- [10] GFZ German Research Centre for Geosciences. (2024). Rain6K: Rainfall variability at the source of the Nile River during the past 6,000 yrs. <https://www.gfz.de/en/section/geomorphology/projects/rain6k-rainfall-variability-at-the-source-of-the-nile-river-during-the-past-6000-yrs>
- [11] Goshu, G., & Aynalem, S. (2017). Problem overview of the Lake Tana Basin. In K. Stave, G. Goshu, & S. Aynalem (Eds.), *Social and ecological system dynamics: Characteristics, trends, and integration in the Lake Tana Basin, Ethiopia* (pp. 9–23). Springer. https://doi.org/10.1007/978-3-319-45755-0_2
- [12] Goshu, G., Koelmans, A. A., & de Klein, J. J. M. (2017). Water quality of Lake Tana Basin, Upper Blue Nile, Ethiopia: A review of available data. In K. Stave, G. Goshu, & S. Aynalem (Eds.), *Social and ecological system dynamics: Characteristics, trends, and integration in the Lake Tana Basin, Ethiopia* (pp. 127–141). Springer. https://doi.org/10.1007/978-3-319-45755-0_10
- [13] Junginger, A., Roller, S., Olaka, L. A., & Trauth, M. H. (2014). The effects of solar irradiation changes on the migration of the Congo Air Boundary and water levels of paleo-Lake Suguta, Northern Kenya Rift, during the African Humid Period (15–5 ka BP). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 396, 1–16. <https://doi.org/10.1016/j.palaeo.2013.12.007>
- [14] Kahmen, A., et al. (2009). Significant seasonal variation in the hydrogen isotopic composition of leaf-wax lipids for two deciduous tree ecosystems. *Organic Geochemistry*, 40*(2), 171–180.
- [15] Kebedew, M. G., Tilahun, S. A., Belete, M. A., Zimale, F. A., & Steenhuis, T. S. (2021). Sediment deposition (1940–2017) in a historically pristine lake in a rapidly developing tropical highland region in Ethiopia. *Earth Surface Processes and Landforms*, 46(8), 1521–1535. <https://doi.org/10.1002/esp.5118>
- [16] Kebedew, M. G., Tilahun, S. A., Zimale, F. A., & Steenhuis, T. S. (2020). Bottom sediment characteristics of a tropical lake: Lake Tana, Ethiopia. *Hydrology*, 7(1), 18. <https://doi.org/10.3390/hydrology7010018>

- [17] Kjellman, S. E., Lapointe, F., Thomas, E. K., Retelle, M. J., & Bradley, R. S. (2024). Improving the leaf wax $\delta^2\text{H}$ paleo-precipitation proxy on Svalbard using annually laminated sediments from Linn évatnet. *Cristin*. <https://app.cristin.no/results/show.jsf?id=2272203>
- [18] Lamb, H. F., Bates, C. R., Coombes, P. V., Baig, M. H., Davies, S. J., Grove, A. T., Jones, R. T., Marshall, M. H., & Umer, M. (2007). Late Pleistocene desiccation of Lake Tana, source of the Blue Nile. *Quaternary Science Reviews*, 26(3–4), 287–299. <https://doi.org/10.1016/j.quascirev.2006.11.005>
- [19] Levin, N. E., Zipser, E. J., & Cerling, T. E. (2009). Isotopic composition of waters from Ethiopia and Kenya: Insights into moisture sources for eastern Africa. *Journal of Geophysical Research: Atmospheres*, 114(D23), D23306. <https://doi.org/10.1029/2009JD012166>
- [20] Liu, J., Liu, W., An, Z., & Yang, H. (2016). Different hydrogen isotope fractionations during lipid formation in higher plants: Implications for paleohydrology reconstruction at a global scale. *Scientific Reports*, 6, 19711. <https://doi.org/10.1038/srep19711>
- [21] Liu, X., Rendle-Bühning, R., Kuhlmann, H., & Li, A. (2017). Two phases of the Holocene East African Humid Period: Inferred from a high-resolution geochemical record off Tanzania. *Earth and Planetary Science Letters*, 460, 123–134. <https://doi.org/10.1016/j.epsl.2016.12.016>
- [22] Marshall, M. H., Lamb, H. F., Huws, D., Davies, S. J., Bates, R., Bloemendal, J., Boyle, J., Leng, M. J., Umer, M., & Bryant, C. (2011). Late Pleistocene and Holocene drought events at Lake Tana, the source of the Blue Nile. *Global and Planetary Change*, 78(3–4), 147–161. <https://doi.org/10.1016/j.gloplacha.2011.06.004>
- [23] Roberts, H. M., Bryant, C. L., Huws, D. G., & Lamb, H. F. (2018). Generating long chronologies for lacustrine sediments using luminescence dating: A 250,000 year record from Lake Tana, Ethiopia. *Quaternary Science Reviews*, 202, 66–77. <https://doi.org/10.1016/j.quascirev.2018.10.037>
- [24] Russell, J. M., Verschuren, D., & Eggermont, H. (2007). Spatial complexity of 'Little Ice Age' climate in East Africa: Sedimentary records from two crater lake basins in western Uganda. *The Holocene*, 17(2), 183–193. <https://doi.org/10.1177/0959683607075832>
- [25] Sutcliffe, J. V., & Parks, Y. P. (1999). *The hydrology of the Nile* (IAHS Special Publication No. 5). IAHS Press.
- [26] Tassew, B. G., Belete, M. A., & Miegel, K. (2021). Assessment and analysis of morphometric characteristics of Lake Tana sub-basin, Upper Blue Nile Basin, Ethiopia. *International Journal of River Basin Management*, 19(4), 195–209. <https://doi.org/10.1080/15715124.2021.1938091>
- [27] Thomas, E. K., et al. (2018). Hydrogen isotope fractionation in leaf waxes in the Alaskan Arctic tundra. *Geochimica et Cosmochimica Acta*, 213, 1–19.
- [28] Tierney, J. E., Pausata, F. S. R., & deMenocal, P. B. (2017). Rainfall regimes of the Green Sahara. *Science Advances*, 3(1), e1601503. <https://doi.org/10.1126/sciadv.1601503>
- [29] Vijverberg, J., Sibbing, F. A., & Dejen, E. (2009). Lake Tana: Source of the Blue Nile. In H. J. Dumont (Ed.), *The Nile: Origin, environments, limnology and human use* (pp. 163–192). Springer. https://doi.org/10.1007/978-1-4020-9726-3_9
- [30] Viste, E., & Sorteberg, A. (2013). Moisture transport into the Ethiopian highlands. *International Journal of Climatology*, 33(1), 249–263. <https://doi.org/10.1002/joc.3409>
- [31] Weiss, H. (2017). Megadrought and collapse: From early agriculture to Angkor. In H. Weiss (Ed.), *Megadrought and Collapse* (pp. 1–41). Oxford University Press. <https://doi.org/10.1093/oso/9780199329199.003.0001>
- [32] Weldegerima, T. M., Zeleke, T. T., Birhanu, B. S., Zaitchik, B. F., & Fetene, Z. A. (2017). Analysis of rainfall trends and its relationship with SST signals in the Lake Tana Basin, Ethiopia. *Advances in Meteorology*, 2017, Article ID 5869010. <https://doi.org/10.1155/2018/5869010>
- [33] Wienhues, G., Lami, A., Bernasconi, S., Jaggi, M., Morlock, M. A., Vogel, H., & Grosjean, M. (2024). Latest Pleistocene and Holocene primary producer communities and hydroclimate in Lake Victoria, eastern Africa. *Quaternary Science Reviews*, 330, 108599. <https://doi.org/10.1016/j.quascirev.2024.108599>
- [34] Woodward, J. C., et al. (2015). The Nile: Evolution, geology and sedimentology. In *Large rivers: Geomorphology and management*.
- [35] Yale Macmillan Center. (2021). *Forever changes: Climate lessons from ancient Egypt*.
- [36] Yasuda, H., Fenta, A. A., Berihun, M. L., Inosako, K., Kawai, T., & Belay, A. S. (2022). Water level change of Lake Tana, source of the Blue Nile: Prediction using teleconnections with sea surface temperatures. *Journal of Great Lakes Research*, 48(2), 468–477. <https://doi.org/10.1016/j.jglr.2022.01.006>
- [37] Younes, M. A., & Bakry, A. (2022). The 4.2 ka BP climate event in Egypt: Integration of archaeological, geoarchaeological, and bioarchaeological evidence. *African Archaeological Review*, 39(3), 315–344. <https://doi.org/10.1007/s10437-022-09487-5>