Review

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Review

Hydrology and Climate Change in Africa: Quaternary Dynamics, Contemporary Challenges, and Future Resilience Pathways

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Abstract: African hydrological systems demonstrate remarkable complexity and sensitivity to climate variability across multiple temporal scales, from profound Quaternary transformations to contemporary water security crises. This narrative review synthesizes paleoclimatic archives, observational data, remote sensing, and climate modeling to unravel the interaction between fluvial processes, water cycle dynamics, and anthropogenic pressures. The Quaternary reveals dramatic shifts, including the African Humid Period (AHP, 11.5-5 ka), which transformed the Sahara into a "pale-green" landscape with expanded wetlands and lakes, terminated by abrupt tipping points signaled by critical slowing down in proxy records. Contemporary systems face accelerating warming (+0.3°C/decade), intensifying hydrological extremes, and regionally divergent responses. East Africa shows reversed temperature-moisture correlations since the Holocene onset, while West African rivers exhibit nonlinear runoff sensitivity (3× reduction per rainfall unit decline). Also, land-use change rivals climate change as a hydrological disruptor, amplifying flood risks and groundwater depletion. Projected aridity, evaporative demands, and aquifer stress mandate integrated adaptation strategies leveraging remote sensing, nature-based solutions, and transboundary governance. We conclude that reconciling paleo-insights with modern vulnerabilities is essential for building resilient water futures across Africa's diverse basins.

Keywords: African hydrology; climate change; water cycling; monsoon dynamics; paleoclimate; arid environments; groundwater resilience; flood generation; remote sensing; water security

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1. Introduction

The hydrological systems of Africa exhibit extraordinary complexity and pronounced sensitivity to climate variability over a vast range of temporal scales. This ranges from immediate water security challenges to long-term environmental transformations dating back to the Quaternary Period (2.6 Ma - present). For example, high-resolution paleoenvironmental reconstructions from eastern South Africa have revealed significant hydrological fluctuations over the past 30,000 years [1], while studies in northern Africa have demonstrated that orbital forcing and land-atmosphere feedback have modulated regional precipitation patterns over millennia [2]. Global assessments have further indicated that Africa's water resources are highly vulnerable to the combined pressures of climate change and rapid population growth [3–5].

Recent observational evidence confirms that Africa is warming at an accelerated pace, approximately +0.3 °C per decade, and these temperature trends, coupled with shifting precipitation regimes, have contributed to the intensification of extreme weather events [6,7]. This has led to an increased frequency and severity of prolonged heatwaves, drought, heavy rainfall, and catastrophic floods that affect various regions of the continent (Table 1) [3,8–10]. Such climatic perturbations disrupt the balance among rainfall, evaporation, and runoff, generating regional hydrological differences that profoundly affect local water availability and ecosystem resilience [4]. In addition to these large-scale climatic shifts, the hydrological responses of Africa are marked by threshold behaviors and non-linear dynamics. Even modest changes in climatic input can trigger rapid shifts

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in water availability when local systems cross critical thresholds. For example, numerical simulations have demonstrated that abrupt, local-scale land-use changes, such as deforestation or overgrazing, can amplify runoff variability and alter evapotranspiration rates (Table 1) [11]. Moreover, integrated modeling studies have shown that the combined impacts of climate change and land–use and land-cover change can lead to non-linear alterations in river flows in key basins [12,13].

Additionally, threshold phenomena in hydrological systems are further explored in studies that document abrupt transitions in flood regimes when critical water level thresholds are exceeded [14]. Moreover, regional case studies underscore the spatial heterogeneity of these hydrological responses. In eastern South Africa, for instance, the Mfabeni peatland record illustrates how past climate variability is reflected in shifts in water table depths and vegetation signals [1]. In contrast, hydrologic modeling applied to the Black Volta River Basin in West Africa has pinpointed critical thresholds beyond which the risk of devastating floods increases sharply [15]. Meanwhile, detailed assessments in sub-Saharan regions reveal that drought dynamics and episodic water scarcity, exacerbated by rapid population growth and land-use pressures, intensify regional differences in water stress [16].

Table 1. Observed and Projected Drought and Flood Trends in African Regions.

Region	Historical Drought Trends	Historical Flood Trends	Projected Trends	Key Implications
Continent-wide	More frequent, intense, widespread droughts (last 50 yrs)	Increased extreme events	Extreme events (heatwaves, floods, droughts) are expected to worsen	Compounding crises, widespread socioeconomic impacts
Sahel	Prolonged dry spells in the 1970s and 1980s		Increased droughts	Food and water insecurity, land degradation, and desertification
East Africa (Horn of Africa)	Severe drought 2011-2012 (worst in	Shift from arid to heavy	Increased temperatures, uncertain	Severe food crisis, displacement, increased risks to

	60 yrs); drying trend 1983-2014	rains/floods in 2019	rainfall (some wetter, some drier)	agriculture/water resources
Southern Africa	Extensive drought 2014-2016, 2019; increased drought frequency	Prone to floods	Extreme weather events are expected to worsen	Reduced agricultural productivity, water availability, and human settlements are vulnerable
Sahara	The highest increasing drought trend across timescales		Increased dryness, potential desert expansion	Heightened vulnerability to extreme aridity, groundwater depletion

The socio-economic implications of these interconnected issues are equally profound, as evidenced in the enhanced climatic extremes and uncertain water flows, leading to fierce competition over scarcer water and arable land. This triggers food insecurity, public health challenges (e.g., increased waterborne diseases), socio-economic vulnerability, and even population displacement [17]. Considering this connection among climatic, biophysical, and socio-economic factors, Africa's hydrological challenges are not isolated phenomena but fundamental drivers of humanitarian crises, regional instability, and economic disruption. Therefore, this narrative review integrates paleo-hydrological records, observational data, and future projections to: (a) investigate Quaternary climate drivers and their legacy in modern landscapes, (b) identify regionally divergent responses of precipitation, evaporation, and groundwater, (c) quantify compounding impacts of climate change and land-use change on African watersheds, and (d) propose resilience-oriented management frameworks for an uncertain future.

2. Paleoclimatic Transformations and Landscape Evolution

2.1. The African Humid Period: Onset, Termination, and Environmental Impacts

The African Humid Period (AHP), occurring roughly between 11,700 and 5,000 years before the present, represents one of the most profound paleoclimatic episodes in Africa's history [18]. During this time, enhanced monsoonal activity led to widespread rainfall that transformed the Sahara from an arid desert into a mosaic of extensive grasslands, woodlands, and numerous lakes, popularly known as the "Green Sahara" [19]. This shift reconfigured African landscapes and had far-reaching

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impacts on human settlement, migration, and cultural development [20]. The termination of the AHP around 5,500 years ago marks an abrupt, threshold-driven transition from a verdant landscape to hyper-arid conditions. High-resolution proxy records, such as the decadal-resolution environmental archive from the Chew Bahir basin in the southern Ethiopian Rift, reveal clear early warning signals and threshold behaviors preceding complete aridification [19,21]. These records indicate that even subtle changes in climatic forcing could trigger dramatic ecosystem shifts, forcing early human societies to adapt their strategies rapidly.

Beyond its historical importance, the AHP is a natural laboratory for investigating abrupt climate transitions and tipping points in Earth's system. Observing the non-linear responses and threshold effects in sedimentary and biological proxy data provides an empirical basis for testing and refining Earth System Models (ESMs). Recent modeling work, leveraging coupled atmosphere-ocean-vegetation simulations, has begun to reproduce many of the transient features observed during the AHP [21–23]. However, the models often underestimate the amplitude of these changes. A further complication is the spatial heterogeneity in the timing and mode of the AHP's termination. Proxy records from different regions of Africa reveal asynchronous responses in vegetation, runoff, and erosion, suggesting that internal feedback and local thresholds modulated the response to the dominant orbital forcing [22,24]. This complex, asynchronous pattern implies that the hydrological and ecological impacts of climate change are highly region-specific.

2.2. *Regional Paleoclimate Reconstructions*

In Southern Africa, Quaternary paleoclimate research has largely focused on determining the timing and extent of aridity/humidity shifts and the relative contribution of temperate versus tropical precipitation sources [25]. Temperature changes, particularly in areas with steep relief gradients or high altitudes, also significantly impacted net moisture availability over glacial-interglacial timescales [25]. Likewise, lake shorelines found tens of meters above present levels, submerged and buried nearshore sedimentary sequences, and fossil and chemical records in East African lake sediments all attest to significant past variations in lake water chemistry and biota in response to shifting rainfall and temperature patterns [26]. For instance, the Last Glacial Maximum (LGM) was predominantly an arid period across most of East Africa, except for the coastal terrain, while wetter conditions did not return until approximately 15,000 years ago (15 ka) [26]. This wet phase was briefly interrupted by a return to drier conditions during the Younger Dryas (12.9-11.7 ka), after which the region experienced the wet AHP that lasted until about 5 ka. Following 5 ka, the region, particularly north of Lake Malawi, became relatively dry again. In contrast, the Lake Malawi basin, situated further south, has exhibited a trend of progressively wetter conditions superimposed on a glacial-dry, interglacial-wet cycle since the Mid-Pleistocene Transition at approximately 900 ka patterns [26]. This regional divergence in climate trends underscores that continental-scale generalizations of climate response are often insufficient.

For the Sahara and North Africa, a significant debate revolves around the existence of "megalakes" during Quaternary humid periods. While some hypotheses suggested the presence of very large lakes, spanning 30,000 to 350,000 km^2, recent evidence indicates that isolated wetlands and smaller lakes are more consistent with the Sahelo-Sudanian paleo-environment that prevailed during the AHP [27]. This implies that the Sahara during the late Quaternary was likely a "pale-green and discontinuously wet" environment rather than a vast interconnected lake system.

Yet, this revised understanding has implications for models of human migration out of Africa, suggesting different ecological corridors were available for early hominins. This highlights the critical need for high-resolution, regionally specific paleoclimate data to accurately reconstruct past environments and their influence on biological and human evolution, emphasizing the limitations of simplistic interpretations of proxy data. Table 2 presents a summary of Quaternary climate periods and hydrological characteristics in Africa.

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Table 2. Summary of Quaternary climate periods and hydrological characteristics in Africa.

Period (Approx. Timeframe)	**Dominant Climate Characteristics**	**Hydrological Features (Regional)**	**Key Drivers / Notes**
Last Glacial Maximum (LGM) (ca. 25-19 ka)	Arid and colder in the Nile headwaters, most of East Africa	Lakes Tana and Victoria dried, White Nile reduced, Blue Nile/Atbara seasonal	Global glacial conditions, reduced monsoon influence
Post-LGM Wetting (ca. 15 ka)	Significant wetting in East Africa	Return of summer monsoon, extreme Blue Nile floods, widespread flooding, formation of large lakes	Return of the summer monsoon
Younger Dryas (YD) (12.9–11.7 ka)	Brief return to drier conditions	Temporary aridity, interruption of the wet phase	Global climatic event
African Humid Period (AHP) (ca. 11.5–5 ka)	Wet, "pale-green and discontinuously wet" Sahara	Lakes expanded across the Sahel/Sahara (e.g., Lake Chad), isolated wetlands/small lakes in the Sahara, and high Nile flow	Enhanced summer monsoon precipitation, northward intertropical convergence zone (ITCZ) displacement

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Post-AHP Drying (after ca. 5 ka)	The region (north of Lake Malawi) became relatively dry again	Reduced Nile sediment discharge, the deep-sea turbidite system is largely inactive	Shift to a more arid continental climate
Mid-Pleistocene Transition (MPT) (ca. 900 ka)	Shift in hydroclimate regimes	Progressively wetter conditions in the Lake Malawi Basin, superimposed on glacial-dry, interglacial-wet cycles	Far-field climate forcing

2.3. Evolution of Paleo-Drainage Networks and River Systems

Despite the contemporary arid to hyper-arid climate that characterizes today's Great Sahara, extensive evidence shows that pluvial climates once dominated the region. During these wetter periods, vigorous rainfall gave rise to expansive paleo-drainage networks, fundamentally altering the landscape. For example, radar remote-sensing data have been instrumental in delineating the now-buried traces of the Trans-African Drainage System and in revealing its linkages with both active and inactive tributaries of the Nile basin, a testament to a time when hydrological connectivity spanned continental scales [28,29]. Furthermore, deep-sea sediment cores recovered from offshore along the Western African margin, currently under the main corridor of Saharan dust plumes, contain distinct fluvial signatures that date back to Marine Isotope Stage 5 (approximately 120,000 years ago) and even earlier. These marine records are particularly valuable because they preserve direct evidence of major river systems that have since disappeared from the landscape, thereby chronicling the hydrological reorganization of the Sahara [29]. This evidence collectively reveals a "hidden history" of African hydrology. Even though much of the continent's past water network is not immediately apparent at the surface, it is preserved in geological archives, ranging from buried riverbeds and ancient lake sediments to deep-sea marine deposits. Nevertheless, accessing and interpreting this concealed record demands advanced methodologies, such as radar imaging, optical remote sensing, and detailed analyses of marine sediment cores. This will elucidate the dramatic transitions between pluvial and arid climates further and also continue to inform predictions of future hydrological and climatic changes in Africa.

2.4. Desert Formation and Fluvial–Aeolian Transitions

As aforementioned, the Saharan landscape experienced remarkable transformations during the Late Quaternary. This transition reflects the cumulative effects of complex interactions among orbital forcing, large-scale atmospheric circulation changes, and vegetation-climate feedback operating

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across multiple timescales [21,24,29]. Fluvial archives offer detailed documentation of the climatic events that have shaped the evolution of the Sahara. For example, the Charef River in the High Plateaus of north-eastern Morocco records two primary incision stages, occurring under hyper-arid conditions around 8,200 and 7,500 calibrated years before the present. These incision events coincide with the globally recognized 8.2 and 7.6-7.3 ka climatic events, demonstrating the acute sensitivity of fluvial systems to rapid climate transitions [30]. Nevertheless, such intense episodes of aridity and simultaneous fluvial incision can destroy or deeply bury earlier environmental records. In effect, the processes that record climatic change also tend to erase or mask prior evidence, thereby introducing preservation biases into the geological archive [31]. This potential data loss underscores the necessity for multi-proxy approaches and for integrating both marine and terrestrial records to construct a complete picture of past environmental variability [32].

The shift from fluvial to aeolian processes marks a fundamental change in landscape evolution in the Sahara. As periods of instability give way to persistent aridity, river systems become truncated, and their sedimentary deposits are increasingly reworked by wind. Such transitions alter erosion patterns, modify sediment-routing systems, and affect the preservation potential of older environmental signals [33,34]. Moreover, the extensive fluvial depositional systems during the African Humid Period now serve as valuable analogs for understanding the geomorphic processes and climate drivers responsible for transitions from wet to arid conditions [34]. In summary, the evolution of the Saharan landscape, from extensive fluvial networks during pluvial episodes to the modern Aeolian-dominated desert, illustrates the dynamic interaction between climate and geomorphic processes.

2.5. Early Warning Signals of Past Environmental Tipping Points

Understanding the early warning signals (EWS) that precede major environmental transitions is critical for evaluating the stability of Earth systems and anticipating potential future climate shifts. A prime example is the 620,000-year-long high-resolution environmental record from the Chew Bahir basin in the southern Ethiopian Rift [21]. This archive demonstrates that the termination of the AHP was not a collapse, but a gradual transition marked by detectable precursors of system instability. In this record, indicators such as increased variance, rising autocorrelation, and prolonged recovery times, collectively called "critical slowing down," preceded the regime shift from humid to hyper-arid conditions [35].

The Chew Bahir record further reveals that EWS can manifest itself in several interrelated ways. For instance, before the final collapse of the AHP, environmental proxies (e.g., isotopic ratios, sedimentological parameters, and biological indicators) showed shifts in their correlation patterns and an increase in the amplitude of fluctuations. These precursors suggest that the system's resilience was gradually eroding, a pattern consistent with theoretical models of tipping points [35,36]. The decadal resolution of this record and the roughly one-thousand-year duration of the transition provide an unprecedented opportunity to analyze the dynamics of gradual change, quantify recovery rates following disturbances, and determine the thresholds at which the system loses stability [20,21]. This shows that understanding these past EWS is valuable for reconstructing historical climate transitions and assessing contemporary climate risks. Consequently, integrating lessons from paleo-records into modern EWS frameworks is essential for developing robust early warning systems and proactive adaptation strategies.

3. Contemporary Hydrological Dynamics and Water Security

3.1. Modern Water Security Challenges and Anthropogenic Influence

The continent's rapidly growing population has increased the demand for freshwater resources, while adverse climate change impacts, especially in sub-Saharan Africa, further reduce water availability. This dual pressure creates a compounding vulnerability, i.e., the increased water demand intensifies stress on systems concurrently experiencing scarcity induced by changing

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precipitation patterns [10]. Moreover, inadequate and aging water infrastructure limits the ability to capture, store, distribute, and manage available resources effectively, and reduces resilience to climate shocks [37]. These interacting factors underscore the necessity of comprehensive, multi-sectoral, and integrated interventions that address climate adaptation, population dynamics, and infrastructural improvements simultaneously rather than in isolation.

In parallel, extensive land-cover changes, whether from deforestation, urban expansion, or the conversion of natural landscapes for agriculture, combined with modifications to surface albedo and shifts in aerosol emissions from both natural and anthropogenic sources, have notably disrupted regional hydrology [12,38,39]. These disturbances have been linked to the increased frequency and severity of drought and flood events in recent decades, with significant implications for societal well-being across the continent. Consequently, the compounded pressures on the hydrological system have rendered freshwater availability an urgent and critical concern [4,40]. Similarly, widespread deforestation for agricultural expansion and grazing removes vegetation cover and significantly alters the emissions of biogenic volatile organic compounds (BVOCs). This reduction in BVOC emissions leads to a decreased burden of biogenic secondary organic aerosols (bSOA), which in turn contributes to a net positive radiative effect (i.e., a warming influence) relative to natural vegetation [41,42]. These changes in atmospheric composition directly affect cloud formation and precipitation patterns, creating a feedback loop where alterations on the surface further modify the atmospheric conditions that control regional hydroclimate.

Therefore, sustainable water management in Africa must go beyond merely improving water use efficiency. It requires a holistic strategy incorporating integrated land-use planning, rigorous emissions control, and comprehensive ecosystem restoration, which stabilizes water resources and mitigates the complex biophysical feedback that links human activities with the stability of the regional water cycle and overall hydroclimate.

3.2. Groundwater Responses to Climate Variability and Human Activities

Groundwater systems across Africa, particularly those in unconfined and shallow aquifers, are sensitive to climate variability and anthropogenic impacts. These aquifers are tightly coupled with surface processes so that changes in precipitation often lead to nearly immediate responses in water-table fluctuations [43]. In sub-humid, semi-arid, and arid regions, evapotranspiration is the second most significant component of the water balance; its magnitude depends not only on water availability but also on shifts in atmospheric demand and vegetation dynamics [11,44–46]. In arid climates, high evapotranspiration rates mean that local precipitation seldom provides effective recharge to groundwater in the plains of inland river basins [4,40]. Instead, these aquifers often depend on recharge from distant mountainous regions, which makes them highly vulnerable to upstream climate variations and remote water management decisions [13,43].

Human activities further complicate these natural processes through intensified agricultural practices, driven by the need to boost crop productivity, frequently leading to overexploitation of groundwater resources. Increased irrigation demands and enhanced actual evapotranspiration associated with agricultural intensification can deplete aquifers faster than natural recharge can occur, thereby pushing coupled river and groundwater systems toward their capacity limits and contributing to widespread water stress in critically water-scarce regions [10,13]. This unsustainable extraction exacerbates the deterioration of both surface and groundwater resources, undermining water security for local communities.

Nonetheless, the substantial yet underutilized potential of Africa's groundwater is concerning. An estimated long-term groundwater recharge across the continent is approximately 15,000 cubic kilometers per decade, even in dryland regions, indicating that, when managed judiciously over decadal timescales rather than on an annual basis, groundwater can serve as a resilient resource for both drinking water and agricultural irrigation [47]. These findings position groundwater as a potential "sleeping giant" that could transform African water security. Moreover, comparative assessments across countries reveal substantial heterogeneity. While many nations exhibit significant

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storage or recharge capacities, a minority (including Eritrea, eSwatini, Lesotho, Zambia, and Zimbabwe) show levels below the continental average and thus require targeted efforts for sustainable development [13]. Therefore, policy and investment must prioritize sustainable groundwater exploration, development, and management to fully capitalize on this resilient resource for long-term water security and climate adaptation.

3.3. Regional Flood Generation Mechanisms and Trends

African flood generation mechanisms are highly heterogeneous because they result from the interaction of regional climatic conditions, antecedent soil moisture, and catchment-specific characteristics. The observed regional variation in flood-generating mechanisms across Africa shows that excess rains on saturated soils dominate in Western Africa, and prolonged "long rains" prevail in Northern and Southern Africa. For instance, a continent-wide analysis of 13,815 flood events across 529 catchments (1981–2018) identified these two processes as responsible for over 75% of flood occurrences, with their spatial patterns closely tied to aridity gradients [48]. In semi-arid regions like the Sahel, excess rainfall on dry, impermeable soils frequently triggers flash flooding. Similarly, prolonged rainfall events in Northern and Southern Africa, often associated with extended monsoon seasons, are exacerbated by climatic variability and land-use changes [49,50].

However, the short length of hydrometric records (typically <40 years) and inhomogeneous data limit robust trend analysis and climate change attribution [51,52]. Meanwhile, recent advances in high-resolution observational networks, including satellite remote sensing combined with in-situ monitoring, have significantly improved our capacity to capture spatial variability in flood extent and antecedent soil moisture in key African watersheds [53–55]. For example, studies employing such networks in West Africa have demonstrated that severe flood events occur when rainfall is coupled with high pre-event soil moisture, emphasizing that flood risk critically depends on rainfall intensity and antecedent moisture conditions. These observational advances facilitate the incorporation of real-time soil moisture data into coupled land-atmosphere and surface–subsurface models, thereby enhancing the predictive skill of flood forecasting systems [56,57]. In parallel, numerical experiments have shown that even modest antecedent soil moisture anomalies can trigger non-linear responses in runoff generation [11]. Such findings highlight that flood generation is controlled by complex feedback between rainfall, soil moisture, and groundwater dynamics that may evolve under future climate change.

Recent climate projections using bias-corrected CMIP6 outputs consistently indicate that Africa will face unprecedented shifts in temperature and extreme precipitation patterns [57–61], underlining that extreme flood magnitudes may increase by over 45% by mid-century under moderate (SSP2-4.5) and high (SSP5-8.5) emissions and land-use scenarios. Such projections underscore the need to move from traditional, solely precipitation-based flood forecasting to integrated approaches that account for antecedent soil moisture, surface and subsurface interactions, and land-use dynamics. This highlights that future research must continue to integrate high-resolution observational networks with fully coupled hydrological models to better quantify the impacts of antecedent soil moisture, remote recharge variability, and land-use change on flood risk and advance our ability to develop resilient, locally tuned flood management strategies.

3.4. Atmospheric and Land-Surface Feedback on the Water Cycle

Various environmental processes, including widespread land-use changes, surface albedo modifications, and aerosol emissions from both natural and anthropogenic sources, strongly perturb the African water cycle. These processes interact in complex feedback loops that can either amplify or dampen climate responses. For example, vegetation cover changes affect the water cycle directly through alterations in evapotranspiration and runoff, and influence atmospheric circulation patterns [4,45,62]. Recent research has shown that deforestation, mainly when driven by the expansion of agriculture and grazing, can lead to substantial reductions in BVOC emissions, especially when converting natural vegetation to agricultural landscapes reduces BVOC emissions by approximately

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26%, which in turn lowers the atmospheric burden of bSOA and creates a net positive radiative effect that contributes to regional warming [42,63]. Conversely, ambitious reforestation and afforestation scenarios may restore BVOC emissions and enhance the bSOA burden, thereby exerting a cooling effect. These dynamics demonstrate that vegetation is not merely a passive recipient of climatic change; it actively modulates local and continental-scale feedback on the water cycle and surface temperature [64,65].

Aerosols further complicate these feedback mechanisms. Desert dust from the Sahara and particles from biomass burning and industrial emissions can alter cloud microphysics and influence precipitation. For instance, recent modeling studies have shown that aerosols can modify cloud properties, either suppressing or enhancing precipitation, depending on local atmospheric conditions [66,67]. In the West African Monsoon region, for example, observed seasonal variations in aerosol optical depth have been strongly correlated with changes in cloud cover and rainfall patterns [68]. These suggest that aerosols exert both direct radiative influences and indirect effects through cloud modification, thereby affecting the regional water balance in ways that remain challenging to predict. Accordingly, modern climate models must incorporate improved representations of aerosol-cloud-precipitation interactions to capture these context-dependent effects accurately [69].

Meanwhile, employing advanced technologies, such as drone-based lidar, photogrammetry, and satellite retrievals, has provided critical insights into spatial variations in surface albedo and vegetation structure across Africa, influencing the understanding of local hydrological cycles [64,65]. These integrated approaches have demonstrated that effective land-use management through reforestation, afforestation, and sustainable agricultural practices can serve as an important adaptation and mitigation strategy with far-reaching impacts on the water cycle [63].

4. Monsoon Dynamics and Regional Hydrological Responses

4.1. East African Monsoon Impacts and River System Sensitivity

East African monsoon systems demonstrate complex responses to multiple forcing mechanisms (e.g., between temperature and moisture) that operate on different timescales, resulting in complex patterns of regional hydrological variability [70,71]. During cooler glacial periods, moisture and temperature exhibited a positive correlation, suggesting that higher temperatures corresponded to increased moisture availability. However, around the onset of the Holocene, approximately 11,700 years before the present, this relationship reversed to become negative as atmospheric carbon dioxide concentrations surpassed 250 parts per million and mean annual temperatures approached modern values [71].

This fundamental shift reflects pronounced changes in both dynamic and thermodynamic aspects of the tropical hydrological cycle. Dynamic processes involving large-scale atmospheric circulation, storm tracks, and precipitation seasonality interact with thermodynamic processes, such as moisture-holding capacity and evapotranspiration rates, producing non-linear responses to temperature changes [3–5,44,72]. Additionally, Eastern African rainfall is modulated by low-latitude insolation and high-latitude glacial-interglacial cycles. Proxy records indicate that Pleistocene rainfall was dominated by insolation forcing, while high-latitude influences strengthened from the last interglacial onward [24,73,74]. Meanwhile, the ongoing drying trends, evidenced by a delayed onset and earlier cessation of the March-May "long rains," have been critical for crop production [75,76].

4.2. West African Monsoon Impacts and River System Sensitivity

West African monsoon systems profoundly influence West African regional hydrology, with even modest variations in rainfall often driving disproportionately large changes in river discharge and groundwater recharge. In semi-arid regions, the non-linear relationship between precipitation and runoff is well documented; for instance, studies have reported that a single-unit decline in rainfall may result in a threefold reduction in runoff [77,78]. This sensitivity originates from the limited soil moisture storage and rapid infiltration losses characteristic of these environments [4,77]. Meanwhile, in the Komadugu-Yobe basin, hydro-meteorological extremes and human activities have exacerbated water stress [55,79–81]. Similarly, flood dynamics have been tied to antecedent soil moisture, i.e., saturated soils amplify flood risks, while deficits reduce runoff generation [82,83]. Likewise, surface-groundwater feedback further amplifies stress as reduced rainfall diminishes both runoff and aquifer recharge [84–86]. Meanwhile, modeling studies predict heterogeneous future responses, with discharge declines in the western Sahel and increases in humid eastern regions [87]. As a result, linear projections of future climate change impacts may considerably underestimate the magnitude of hydrological shifts, presenting a significant challenge for regional water resource planning.

5. Future Projections and Water Resource Management

5.1. Climate Change Projections for African Basins

Future climate projections for African basins indicate that hydrological processes will experience substantial alterations, with far-reaching implications for water resource management and ecosystem sustainability (Table 3). Under continued global warming, many studies suggest that Africa will face increasing aridity and associated reductions in overall water availability [4,5,10]. However, most traditional freshwater assessments have focused on single hydroclimatic variables, such as precipitation or runoff, without simultaneously accounting for evaporative demand and changes in soil moisture storage. This segmented approach generates high uncertainty in basin-scale water projections and underscores the urgent need for more holistic, integrated climate impact assessments [37].

Other studies illustrate the projected hydrological impacts in specific African basins using compound approaches. For example, the Gilgel Gibe catchment in southwest Ethiopia and the Vea catchment in Ghana show projected declines in precipitation coupled with rising temperatures, leading to significant reductions in surface runoff, groundwater recharge, and overall water yield. These projections are derived from ensemble outputs of Regional Climate Models (RCMs) participating in the Coordinated Regional Climate Downscaling Experiment (CORDEX)-Africa and are typically assessed with hydrological models such as the Soil and Water Assessment Tool (SWAT) [88–90].

Despite notable advances in RCMs, significant local-scale uncertainties persist. These arise from unresolved small-scale processes, inherent model biases, and the limited spatial resolution of downscaled climate projections [4,59]. Many aimed to mitigate these issues and improve the reliability of projections using multi-model ensembles [91,92] in conjunction with bias correction and downscaling techniques [4,58,61,89,93,94]. Such methodological advancements have enhanced our capacity to simulate present-day climate extremes and provided more robust predictions of future hydrological variability [79].

Furthermore, the implications of these climate-induced changes in water availability extend well beyond hydrology alone. Water resources are deeply intertwined with the energy and food sectors, a relationship encapsulated in the water-energy-food (WEF) nexus, as changes in water availability directly influence agricultural productivity and hydropower generation. This raises concerns about food and energy security across the continent [95]. In summary, future climate projections indicate that African basins will likely experience pronounced increases in aridity, reduced water yields, and amplified hydrological variability. These changes will challenge traditional water resource management practices and necessitate adopting integrated, multi-sectoral adaptation strategies.

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Table 3. Projected Climate Change Impacts on Major African River Basins.

River Basin	Projected Changes in Precipitation	Projected Changes in Evapotranspiration (ET)	Projected Changes in River Flow (climate change [CC] only)	Influence of Land-use Change (LULCC) on River Flow	Key Implications
Nile	Mixed signals	Increase	Mixed signals	Not explicitly detailed, but general LULCC impacts are noted for Africa	High uncertainty in future flows, increased evaporation, reduced water availability for agriculture
Congo	Variable: increase in NW/SE, decrease in center/south	Decline under RCP2.6, milder changes under combined drivers	Reduced flows	+18% increase with LULCC vs. >20%	Significant impacts on agriculture, hydropower, water availability;

				decrease without	deforestation is a major concern
Niger	Increase under CC alone (e.g., +44 to +50 mm/yr)	Not explicitly detailed, but ET plays a substantial role in water availability	Largest decrease in Africa due to CC	Reduction in water availability under RCP6.0/8.5 with LULCC	Further desertification in northern West Africa, threatening livelihoods
Zambezi	Slight increase in average rainfall, but high variability	Negative signal under all RCPs	Reduced flows	Minimal impact due to mild LULCC; can show increases due to lower simulated historical values	Increased flow variability, more floods/droughts, impact on agriculture/energy, need for coordination
Limpopo	Not explicitly detailed, but some studies	Not explicitly detailed, but ET plays a	Higher river flows	River flows increase from CC scenarios	Increased flow variability, more floods/droughts, impact on agriculture/energ

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	show higher flows	substantial role in water availability	are likely	under all RCPs, largest increase in monthly flow during wet months under RCP6.0	y, need for coordination

5.2. Remote Sensing Applications for Hydrological Monitoring

Remote sensing applications have emerged as a cost-effective and increasingly indispensable tool for monitoring terrestrial water cycles and supporting hydrological investigations across Africa [96,97]. With traditional, ground-based monitoring networks being sparse and often inadequate [51], satellite-based observations now provide unprecedented spatial and temporal coverage of critical hydrological variables. This comprehensive observational capability is essential for bridging data gaps in many African basins and informing hydrological models and water resource management decisions [40,44,54,69,96,98,99].

Recent advances in Earth observation technologies, including optical, multispectral, microwave, and radar sensors, have enabled a systematic assessment of changes in lakes, rivers, groundwater storage, and soil moisture. For example, satellites have been used to track variations in lake levels and terrestrial water volume over time, providing essential data to quantify regional water budgets and understand seasonal and interannual variability under changing climatic conditions [4,96,100–107]. Innovative multi-sensor fusion approaches have enabled the integration of datasets from different satellite missions to produce high-resolution, comprehensive monitoring products [93,99]. Over the past decade, major satellite missions have revolutionized hydrological monitoring over Africa. The Gravity Recovery and Climate Experiment (GRACE) and its follow-on (GRACE-FO) have provided transformative insights into changes in total water storage, thereby offering a means to detect groundwater depletion and recharge processes at continental scales [96,100,105]. Other notable advancements leveraging remote sensing data include the high-resolution discharge datasets, VegDischarge, which covers over 64,000 segmented river reaches across Africa [108], which enhances water security assessments and supports the design of adaptive management strategies in regions where in-situ measurements are limited.

Moreover, integrating multi-sensor observations with advanced modeling techniques will further improve our ability to quantify key hydrological processes. For example, machine learning algorithms are now being applied to these rich datasets to detect subtle, non-linear responses of the terrestrial water cycle and other climate extremes to climate and land-use changes [4,93,109,110]. These integrated approaches will improve the accuracy of hydro-meteorological forecasts and

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facilitate the development of operational monitoring systems that are vital for water resource planning and drought or flood early warning.

5.3. Adaptation Strategies and Policy Implications

Successful adaptation to changing hydrological conditions across Africa requires integrated, multi-scale approaches that account for both gradual trends and abrupt extremes. A fundamental prerequisite for evidence-based decision-making in water resource management, agriculture, and environmental conservation is an in-depth understanding of hydrological processes, including evapotranspiration, soil moisture dynamics, surface runoff, and river discharge, which operate over diverse spatial and temporal scales [4,10,37]. Because these processes are inherently non-linear, even relatively small climate changes can disproportionately affect water availability. Hence, adaptation strategies must be flexible and capable of responding to multiple future scenarios rather than relying solely on single best-estimate projections.

Comprehensive hydrological modeling is increasingly important in developing improved water management techniques. Such models need to incorporate both dynamic processes (e.g., shifts in atmospheric circulation and storm track variability) and thermodynamic processes (e.g., changes in moisture-holding capacity and evapotranspiration rates), as well as the complex feedback among vegetation, atmosphere, and hydrology [110]. Nevertheless, integrating remote sensing observations with these process-based models will further enhance our capacity to monitor key hydrological variables and to improve predictions of water availability under a changing climate.

Additionally, proactive adaptation measures are essential for mitigating the impacts of climate change on water resources in various African basins. These measures must address gradual shifts in mean hydrological conditions and the increased variability and intensity of extremes such as droughts and floods. Even though multi-model ensemble studies and rigorous bias-correction techniques have improved our understanding of potential future hydrological changes, uncertainties remain, particularly at local scales [4,111]. Consequently, developing and implementing robust early warning systems for drought and flooding are crucial adaptation priorities, as they protect lives, safeguard infrastructure, and support sustainability in regions highly vulnerable to climate extremes [56]. Additionally, nature-based solutions provide promising pathways for climate resilience by leveraging ecological processes to mitigate water stress. For example, green infrastructure, including green roofs, urban parks, wetlands, and forests, can improve stormwater management, reduce flood risk, and enhance groundwater recharge [95]. Restoring natural ecosystems such as mangroves, salt marshes, and coral reefs also offers cost-effective coastal protection and supports biodiversity, while riverbank re-greening provides a viable alternative to conventional river training for reducing flood risks. In many cases, hybrid "green-gray" approaches that combine engineered and nature-based solutions offer the versatility needed to enhance overall water resilience. Furthermore, cooperative water management in transboundary basins is essential for achieving sustainable development, reducing conflict risks, and enhancing regional resilience [55,80]. Initiatives such as the Niger Basin Authority demonstrate the benefits of coordinated, basin-wide management for balancing competing water demands and for jointly addressing climate-induced variability.

Ultimately, tackling Africa's water security and climate challenges requires strategic planning and considerable investment in resilient infrastructure. This involves strengthening hydrometeorological networks and institutional capacity for data collection and forecasting and integrating the water–energy–food nexus into adaptation strategies that enhance the overall resilience of African basins in the face of climate change.

6. Conclusions

This review demonstrates that African hydrology exhibits extraordinary complexity and sensitivity across various temporal scales, from modern observations to Quaternary paleoclimatic reconstructions. The continent's water systems display distinct threshold behaviors, non-linear responses, and asynchronous regional patterns that challenge simplistic climate-hydrology

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paradigms. These characteristics demand sophisticated analytical tools and adaptive management strategies to address water security sustainably amid rapid environmental changes.

A key finding is the fundamental shift in temperature-moisture relationships in eastern Africa. During the cooler glacial periods, effective moisture and temperature were positively correlated; however, around the onset of the Holocene, when atmospheric CO_2 levels surpassed approximately 250 parts per million and mean annual temperatures approached modern levels, this relationship reversed to a negative correlation. Such a pivotal change implies that continued warming will likely exacerbate moisture deficits, directly threatening water security, agriculture, and ecosystem sustainability. The AHP and its termination are major continental-scale environmental transitions that provide critical analogs for understanding abrupt hydrological transformations. While detecting early warning signals offers invaluable insights into the potential for future climatic tipping points under anthropogenic forcing, the extensive fluvial deposits in current hyperarid landscapes vividly document the magnitude of past hydrological restructuring.

Contemporary African water systems face unprecedented pressures due to rapid population growth, climate change, and altered precipitation regimes, which disrupt traditional flood generation mechanisms and groundwater recharge processes [112] and underscore the vulnerability of African basins. The spatial variability of these processes reinforces the need for locally tailored management strategies rather than uniform, continent-wide approaches.

Future research should prioritize the integration of high-resolution multiproxy records, including lake sediments, speleothems, and terrestrial archives, with fully coupled climate-hydrological models. Also, applying advanced quantitative methods (e.g., artificial intelligence) will be essential for capturing subtle non-linear responses in basin-scale water projections. Moreover, incorporating a comprehensive water-energy-food nexus framework into policy and adaptation planning is critical for developing robust, sustainable strategies to address the multifaceted challenges of climate change across Africa's diverse basins.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	African Humid Period
RCP	Representative Concentration Pathway
ESM	Earth System Models
LGM	Last Glacial Maximum
MPT	Mid-Pleistocene Transition
YD	Younger Dryas
EWS	Early Warning Signals
BVOC	Biogenic Volatile Organic Compound
CMIP6	Coupled Model Intercomparison Project Phase 6
RCM	Regional Climate Model
SWAT	Soil and Water Assessment Tool
WEF	Water-Energy-Food
CC	Climate Chan
ET	Evapotranspiration
LULCC	Land-use change
CORDEX	Coordinated Regional Climate Downscaling Experiment
GRACE	Gravity Recovery and Climate Experiment
bSOA	Biogenic secondary organic aerosols

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