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Review

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

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Abstract

African hydrological systems are incredibly complex and highly sensitive to climate variability. This review synthesizes observational data, remote sensing, and climate modeling to understand the interactions between fluvial processes, water cycle dynamics, and anthropogenic pressures. Currently, these systems are experiencing accelerating warming (+0.3 °C/decade), leading to more intense hydrological extremes and regionally varied responses. For example, East Africa has shown reversed temperature–moisture correlations since the Holocene onset, while West African rivers demonstrate nonlinear runoff sensitivity (a threefold reduction per unit decline in rainfall). Land-use and land-cover changes (LULCC) are as impactful as climate change, with analysis from 1959–2014 revealing extensive conversion of primary non-forest land and a more than sixfold increase in the intensity of pastureland expansion by the early 21st century. Future projections, exemplified by studies in basins like Ethiopia's Gilgel Gibe and Ghana's Vea, indicate escalating aridity with significant reductions in surface runoff and groundwater recharge, increasing aquifer stress. These findings underscore the need for integrated adaptation strategies that leverage remote sensing, nature-based solutions, and transboundary governance to build resilient water futures across Africa's diverse basins.

Keywords: African hydrology; climate change; water security; groundwater resilience; flood generation; ecosystem-based adaptation; land-use land-cover change

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1. Introduction

The hydrological systems of Africa exhibit extraordinary complexity and pronounced sensitivity to climate variability, presenting immediate water security challenges and long-term environmental changes. High-resolution observational studies from eastern South Africa have revealed significant hydrological fluctuations over recent decades [1], while studies in northern Africa have demonstrated that regional precipitation patterns are increasingly modulated by anthropogenic climate change [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 [3,4].

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 [5]. 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) [4,6,7]. Such climatic perturbations disrupt the balance between rainfall, evaporation, and runoff, generating regional hydrological differences that profoundly affect local water availability and ecosystem resilience [8,9]. Beyond large-scale climatic shifts, Africa's hydrological responses are notably shaped by threshold behaviors and nonlinear dynamics. Even minor shifts in climatic input can trigger rapid changes in water availability as local systems cross critical thresholds. For instance, numerical simulations show that abrupt, local LULCC, like deforestation or overgrazing, amplify runoff variability and alter evapotranspiration rates (Table 1) [10]. Furthermore, integrated modeling studies reveal that the combined impacts of climate change and LULCC lead to nonlinear alterations in river flows within key basins [3]. These dynamics are also influenced by elevation differences (Figure 1), which delineate distinct systems and drive varied responses to climate variability.

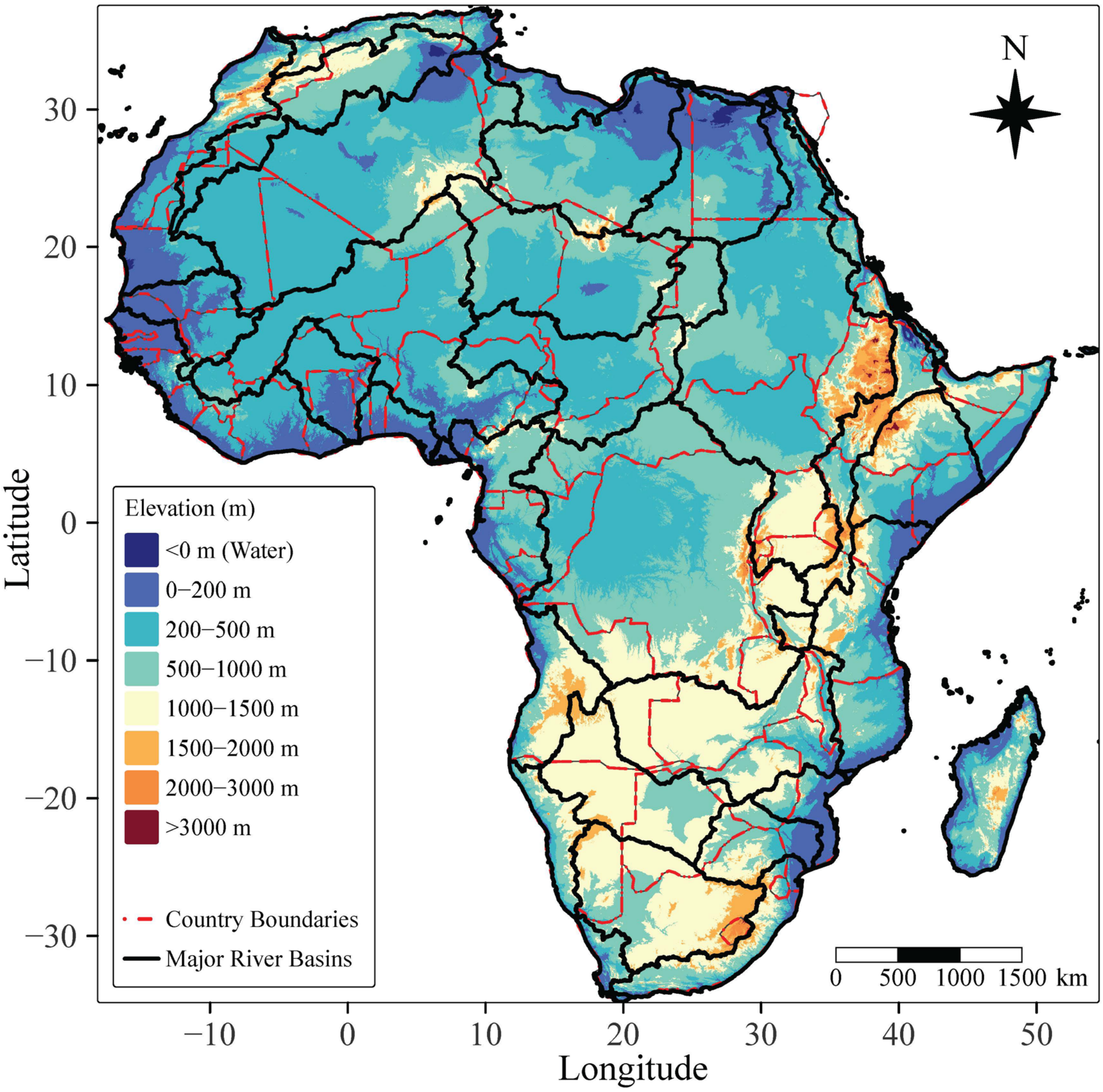

Figure 1. Major river basins in Africa with their associated elevations. The solid black lines are the river basins, while the dotted red lines are the boundaries of the African countries.

These threshold phenomena are also evident in abrupt transitions in flood regimes when critical water level thresholds are exceeded [11]. Regional case studies further underscore the spatial heterogeneity of these hydrological responses. For example, the Mfabeni peatland record in eastern South Africa illustrates how past climate variability is reflected in shifts in water table depths and vegetation signals [12]. Similarly, hydrologic modeling of the Black Volta River Basin in West Africa has pinpointed critical thresholds that sharply increase the risk of devastating floods [13]. Meanwhile, detailed assessments across sub-Saharan regions reveal that drought dynamics and episodic water scarcity are intensifying regional water stress, a problem exacerbated by rapid population growth and LULCC [14].

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, and widespread droughts observed over last 50 years, with notable droughts during 1970s–90s [15].	Increased frequency and intensity of extreme flood events in various basins including Niger and Zambezi [16].	Extreme events (heatwaves, floods, droughts) expected to worsen, linked to climate change projections [17].	Compounding crises leading to widespread socio-economic impacts; stresses on agriculture, water, and infrastructure.
Sahel	Prolonged dry spells during the 1970s and 1980s causing major drought crises; increasing drought tendencies persist [18,19].	Some instances of flooding, particularly in the Gulf of Guinea and Savannah zones; variability in wet/dry extremes noted [20].	Increased drought frequency and severity projected; desertification and land degradation likely to intensify [17,21].	Worsened food and water insecurity, accelerated land degradation, and desertification threatening livelihoods.
East Africa (Horn)	Severe drought in 2011–2012 (worst in 60 years) and a drying trend from 1983 to 2014; regionally variable drought hotspots exist [22].	Shift towards heavy rains and floods as seen in 2019–2020, linked to positive Indian Ocean Dipole (IOD) events [23].	Rising temperatures with uncertain rainfall patterns; some areas wetter, others drier [8,17].	Severe food crises, displacement, heightened risks to agriculture and water resources requiring adaptive strategies.
Southern Africa	Notable extended droughts in 2014–2016 and 2019; drought frequency increasing [14].	Region prone to floods in river valleys and urban areas; increased extreme precipitation events documented [16].	Extreme weather events including both droughts and floods expected to worsen; drier conditions to intensify [17].	Reduced agricultural productivity, water scarcity, and vulnerability of human settlements, necessitating integrated adaptation.
Sahara	Highest observed increase in drought trends across multiple timescales; persistent aridity intensification [15].	Flooding rare but possible flash floods are under-documented due to sparse data.	Continued dryness and potential desert expansion; groundwater depletion likely [17].	Heightened vulnerability to extreme aridity and water resource depletion; significant challenges for sustaining populations and ecosystems.

The socio-economic implications of these interconnected hydrological issues are profound. Enhanced climatic extremes and uncertain water flows intensify competition over increasingly scarce water and arable land. This, in turn, triggers food insecurity, public health challenges (e.g., increased waterborne diseases), socio-economic vulnerability, and even population displacement [24]. Considering these deep connections among climatic, bio-physical, and socio-economic factors, Africa's hydrological challenges are not isolated phenomena; rather, they are fundamental drivers of humanitarian crises, regional instability, and economic disruption.

This review addresses critical gaps in understanding contemporary African hydrology by providing a synthesis of recent research findings and future projections. Its significance lies in its integrated approach, which examines multiple stressors affecting African water systems, including climate change, LULCC, and socio-economic pressures. Unlike previous reviews that often focus on single aspects, this study offers a comprehensive framework for understanding the complex interactions between natural and anthropogenic drivers of hydrological change.

Specifically, the review aims to (a) synthesize contemporary hydrological challenges across African regions, (b) identify regionally divergent responses of precipitation, evaporation, and groundwater systems, (c) quantify compounding impacts of climate change and LULCC on African Basins, and (d) propose evidence-based resilience frameworks for sustainable water management.

2. Evolving Research Landscapes in African Hydrology

A quantitative bibliometric analysis of African hydrology research from 2019 to 2024, using data from Scopus and Web of Science, reveals evolving thematic priorities and methodological approaches. Through keyword co-occurrence analysis, five distinct research clusters are identified, delineating the shifts in scholarly focus over this period (Figure 2a). The analysis of these clusters shows clear trends. "Water management and supply" remained the largest research area, though its proportion of scholarly output saw a marginal decrease from 35% in 2019 to 32% by 2024. In contrast, publications related to "Climate change and adaptation" demonstrate steady growth, increasing from 25% to 28%, reflecting heightened attention to climate resilience. The "Hydrological modeling and remote sensing" cluster consistently constitutes 20% of the output, highlighting its persistent role as a core methodology. Research on "Extreme events and risk assessment" also saw a slight rise from 15% to 16%, signaling a growing focus on disaster mitigation. Finally, "Ecosystem services and nature-based solutions" emerge as a smaller but distinct cluster, representing 5% of publications in 2019 and declining slightly to 4% by 2024.

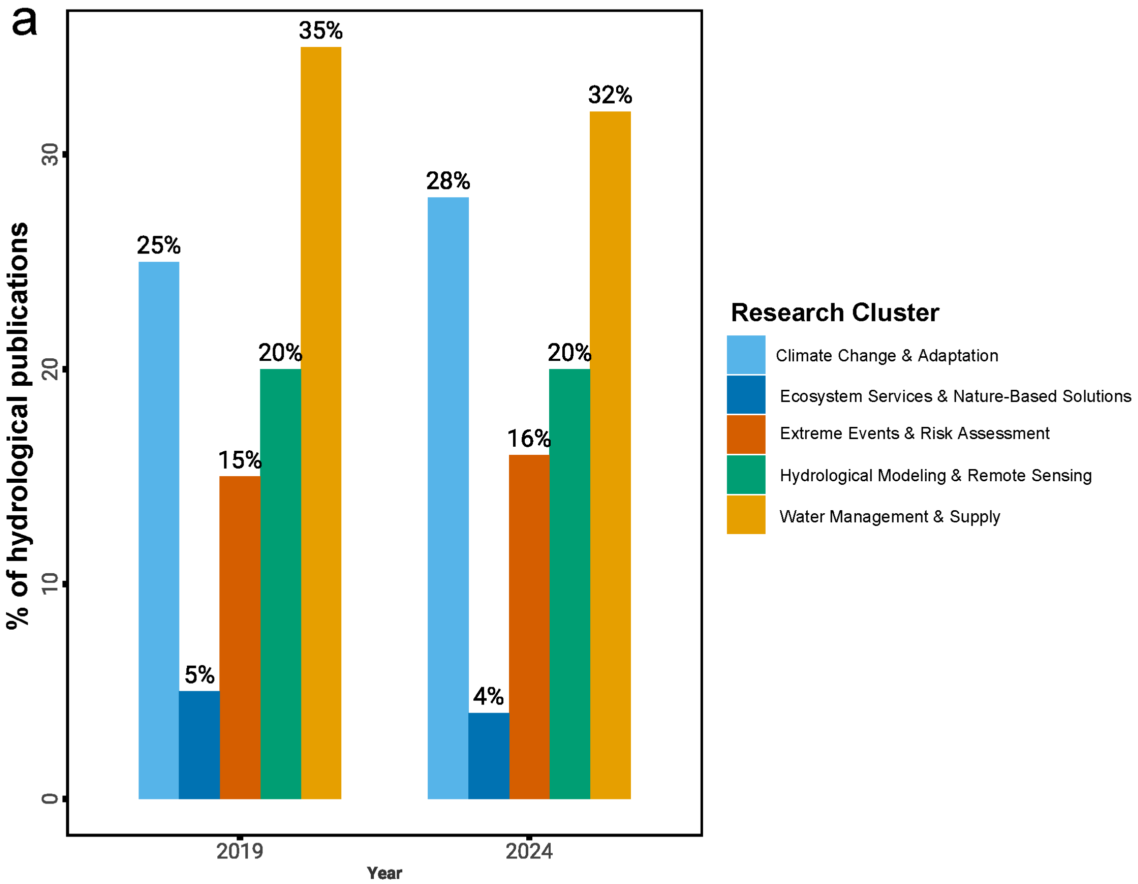

Figure 2. *Cont.*

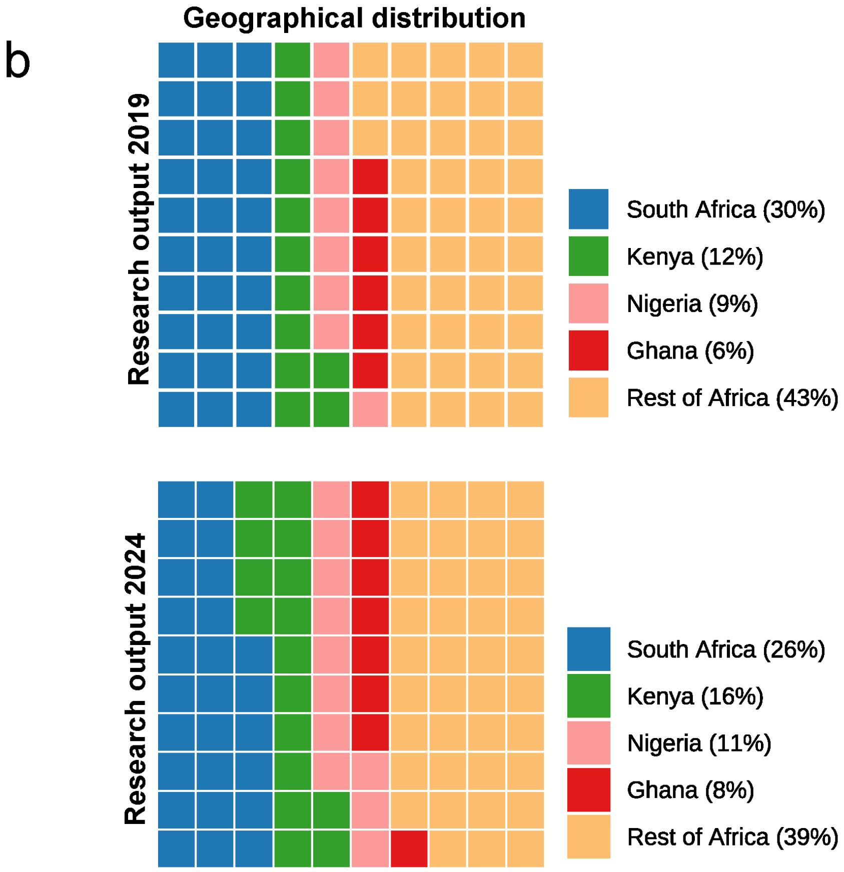

Figure 2. African hydrology research trends (**a**) Research clusters and (**b**) Geographical distribution of research output. Each square in the lower charts represents 1% of continental hydrological research output.

Geospatial analysis (Figure 2b) further illuminates shifting research capacities across the continent. While South Africa consistently dominated output (30% in 2019; 26% in 2024), significant growth is observed from Kenya (12% to 16%), Nigeria (9% to 11%), and Ghana (6% to 8%). This expansion, however, contrasts with a collective decline from the rest of Africa (43% to 39%), underscoring persistent regional disparities in research output. These insights into shifting thematic priorities and regional capacities serve as a critical baseline for future research directions and policy development.

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 precipitation patterns [7]. Moreover, inadequate and aging water infrastructure limits the ability to capture, store, distribute, and manage available resources effectively, and reduces resilience to climate shocks [25]. These interacting factors underscore the necessity of comprehensive, multi-sectoral, and integrated interventions that address climate adaptation, population dynamics, and infrastructural improvements simultaneously.

In parallel, extensive LULCC—including deforestation, urban expansion, and agricultural conversion—has significantly disrupted regional hydrology [26–28]. For instance, Figure 3 illustrates LULCC across Africa over five 11-year rolling periods: 1959–1970 (Period 1), 1970–1981 (Period 2), 1981–1992 (Period 3), 1992–2003 (Period 4), and 2003–2014 (Period 5). This analysis follows the methodology of Adeyeri et al. [29]. To clarify terms, primary land refers to natural vegetation (forest or non-forest) untouched by human activities. Secondary land, conversely, is naturally regrowing vegetation (forest or non-forest) that has experienced prior human disturbance. It is important to note that even mature secondary lands are assumed not to revert to a primary condition in this analysis.

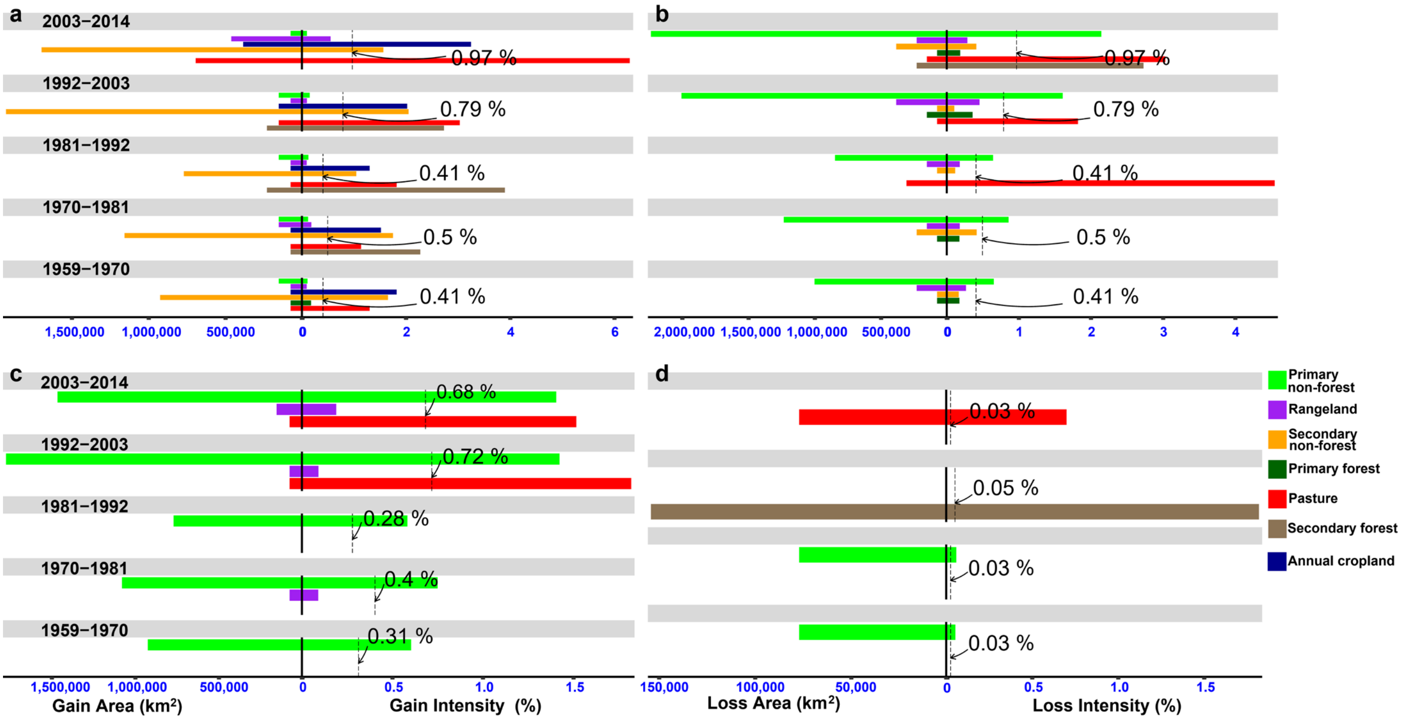

Figure 3. Categorical intensities of all LULC types (**a**,**b**), and Transition intensities for (**c**) secondary non-forest (**d**) primary forest between 1959 to 2014. Active transitions are the areas extending beyond the uniform rate line, while passive/dormant transitions fall below the uniform rate line [29].

During Period 1 (1959–1970; Figure 3a), secondary non-forest experienced the most significant area gain (~1 million km^2), while rangeland saw the least. Although the uniform intensity gain was 0.4%, annual cropland, pasture, and secondary non-forest all recorded gain intensities exceeding 1%. This trend continued in Periods 2 and 3, with secondary non-forest maintaining the largest gained area (>1 million km^2), but secondary forest recording the highest gain intensity (over 2%). Period 3 showed increased gains in both area and intensity. By Period 4, secondary non-forest gained the largest area (2 million km^2), while pasture recorded the most active gain intensity. Pasture continued this pattern in Period 5 with the highest gain intensity, exceeding 6%. Regarding losses (Figure 3b), primary non-forest experienced the greatest overall area loss throughout all periods, but pastureland consistently showed the most active loss intensity, particularly from Period 3 onward. Examining transitions, secondary non-forest gain (Figure 3c) primarily originated from primary non-forest across all sub-periods, ranging from ~1 million km^2 in Period 1 to >1.5 million km^2 in Period 4. However, its most active gain intensity source shifted to pasture in Periods 4 and 5, exceeding 1.5%. Primary forest losses (Figure 3d) consistently led to gains in primary non-forest, secondary forest, and pasture, with the most active loss intensities directed toward secondary forest and pasture.

These disturbances have been linked to the increased frequency and severity of drought and flood events in recent decades, severely impacting societal well-being across Africa. Consequently, the combined pressures on the hydrological system have made freshwater availability an urgent and critical concern [8]. Furthermore, widespread deforestation for agriculture and grazing reduces biogenic volatile organic compound (BVOC) emissions, decreasing the biogenic secondary organic aerosol (bSOA) burden and causing a net positive radiative effect (warming) relative to natural vegetation [30,31]. These atmospheric changes directly affect cloud formation and precipitation patterns, creating a feedback loop that further modifies regional hydroclimate.

Consequently, sustainable water management requires a holistic strategy beyond improved water efficiency, incorporating integrated land-use planning, rigorous emissions control, and comprehensive ecosystem restoration to stabilize water resources and mitigate the biophysical feedback linking human activities to water cycle stability. This heightened pressure on surface water availability, exacerbated by anthropogenic activities, inherently shifts towards Africa's critical groundwater reserves.

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 [32]. 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 [10,33,34]. In arid climates, high evapotranspiration rates mean that local precipitation seldom provides effective recharge to groundwater in the plains of inland river basins [8,35]. 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 [3,32].

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 [3,7]. 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 worrying. 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 [36]. 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 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 [3]. 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.

While groundwater offers crucial resilience against water scarcity, extreme hydrological events, particularly floods, present a contrasting challenge, demanding distinct understanding and management strategies across the diverse African landscape.

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 [37]. 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 LULCC [38,39].

However, the short length of hydrometric records (typically <40 years) and inhomogeneous data limit robust trend analysis and climate change attribution [19,40]. 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 basins [41,42]. 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 [43,44]. In parallel, numerical experiments have shown that even modest antecedent soil moisture anomalies can trigger non-linear responses in runoff generation [10]. 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 [43,45–47], 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 LULCC on flood risk and advance our ability to develop resilient, locally tuned flood management strategies.

Crucially, the dynamics of flood generation and water security are not solely governed by direct climatic inputs but are also strongly shaped by complex interactions between the atmosphere and the land surface.

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

Various environmental processes, including widespread LULCC, 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 [8,34,48]. 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 26%, which in turn lowers the atmospheric burden of bSOA and creates a net positive radiative effect that contributes to regional warming [31,49]. 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 [50,51].

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 [52,53]. 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 [54]. 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 [55].

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 [50,51]. 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 [49].

Yet, understanding these broader land–atmosphere interactions is crucial, as they fundamentally shape the continent's major climatic systems, including the critically important monsoon dynamics that drive much of Africa's regional hydrological responses.

4. African Monsoon Dynamics and Regional Hydrological Impacts

4.1. East African Monsoon Impacts and Hydrological Variability

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 [56,57]. 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 [57].

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 [4,8,58,59] 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 [60–62]. 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 [63,64].

4.2. West African Monsoon Variability and Hydrological Sensitivity

West African monsoon systems strongly influence West African regional hydrology, with even modest variations in rainfall often driving disproportionately large changes in river discharge and groundwater recharge. This is particularly evident in semi-arid regions, where a well-documented non-linear relationship between precipitation and runoff means a single-unit decline in rainfall can result in a threefold reduction in runoff [65,66]. This sensitivity originates from the limited soil moisture storage and rapid infiltration losses characteristic of these environments [8,65]. Beyond this inherent sensitivity, various interconnected factors amplify water stress. Flood dynamics, for instance, are strongly tied to antecedent soil moisture: saturated soils amplify flood risks, while deficits reduce runoff generation [67,68]. Similarly, surface-groundwater feedback further exacerbates stress, as reduced rainfall diminishes both runoff and aquifer recharge [35,69–71]. These hydro-meteorological extremes, coupled with human activities, have notably intensified water stress, as widely observed in basins like Komadugu-Yobe [28,72,73].

Given these complex non-linear dynamics, modeling studies predict heterogeneous future responses across the region, with discharge declines anticipated in the western Sahel contrasting with potential increases in humid eastern regions [74]. Consequently, linear projections of future climate change impacts may considerably underestimate the true magnitude of hydrological shifts, thereby presenting a significant challenge for regional water resource planning. Building upon this understanding of complex regional monsoon dynamics and their historical and contemporary sensitivities, it becomes imperative to comprehensively examine overarching future climate projections and their profound implications for long-term water resource management across Africa.

5. Future Projections and Water Resource Management

5.1. Climate Change Projections for African Basins

Future climate projections indicate that African basins will likely experience substantial alterations, including pronounced increases in aridity, reduced water yields, and amplified hydrological variability (Table 2). These changes challenge traditional water resource management and necessitate a shift toward holistic, integrated climate impact assessments that move beyond single-variable analyses (e.g., only precipitation or runoff) to account for evaporative demand and soil moisture simultaneously [7,8,58]. The deep interconnection between water, energy, and food security—the WEF nexus—further heightens the urgency, as changes in water availability directly influence agricultural productivity and hydropower generation across the continent [75]

For example, studies using ensemble outputs from Regional Climate Models (RCMs) in the Coordinated Regional Climate Downscaling Experiment (CORDEX)-Africa experiment, coupled with hydrological models like the SWAT, project significant declines in precipitation and rising temperatures in catchments such as the Gilgel Gibe in Ethiopia and the Vea in Ghana. This combination is expected to lead to significant reductions in surface runoff, groundwater recharge, and overall water yield [76–78]. While methodological advancements like multi-model ensembles and bias correction have improved the reliability of these projections [8], significant local-scale uncertainties persist due to unresolved small-scale processes and model biases [21,35,76,79]. Nonetheless, the consistent projection of a drier future with more extreme variability underscores the need for adopting integrated, multi-sectoral adaptation strategies to ensure future water security.

Table 2. 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 Only)	Influence of LULCC on River Flow	Key Implications
Nile	Mixed signals with inter-annual and spatial variability, with the most significant increases in the rainy season and a significant decrease in the dry season [80]. The results suggest the probability of an increase in total precipitation.	Increase in evapotranspiration leading to higher atmospheric evaporative demand [80]	Mixed signals with likely increases in total river flow and peak discharges [80]	General LULCC impacts noted for Africa with accepted considerations of land uses at 52% of the cases [81]	High uncertainty in future flows, increased evaporation, reduced water availability for agriculture, higher risk of floods and droughts in the future
Congo	Increase in northwest/southeast regions, decrease in left/south with decline under RCP2.6 [3]	Decline under RCP2.6, milder changes under combined drivers when investigating how evapotranspiration responds to both climate change and LULCC scenarios [3]	Reduced flows with up to 7% decrease under climate change [3]	Largest difference between scenarios: +18% increase with LULCC vs. >20% decrease without LULCC [3]	Significant impacts on agriculture, hydropower, and water availability; deforestation is a major concern requiring policies to combat the current trend of deforestation
Niger	Increase under climate change alone (+44 to +50 mm/yr) with a reduction in discharge volume at the beginning of the high flow period, explained by a delayed start of the rainy season [82]	Substantial role in water availability with evapotranspiration impacts that should be interpreted cautiously [81]	Largest decrease in river flows in all of Africa due to climate change [3] with projected decreases of 5–12 m^3/s under RCP 4.5 and 36–52 m^3/s under RCP 8.5 [82]	Reduction in water availability under RCP6.0/8.5 with LULCC effects requiring policies to halt global greenhouse gas emissions [3]	Further desertification in northern West Africa, threatening livelihoods and requiring improved water management schemes within the context of a changing climate.
Zambezi	Slight increase in average rainfall but high variability with drying trends and shorter, more variable seasons experiencing prolonged drought periods [83]	Negative signal under all RCPs with increasing evapotranspiration as changes in temperature and rainfall have a direct effect on the quantity of evapotranspiration [83]	Reduced flows with up to 7% decrease [3] and reduction in average annual stream flow [83]	Minimal impact due to mild LULCC; can show increases due to lower simulated historical values [3]	Increased flow variability, more floods/droughts, significant warming, prolonged drought periods and extreme floods with the basin experiencing one of the most variable climates of any major river basin in the world
Limpopo	Mixed projections with some studies showing potential for higher river flows [3], and modellers managed to understand and build robust rainfall-runoff relationships in Limpopo [81]	Substantial role in water availability with evapotranspiration impacts that should be interpreted cautiously [81]	Higher river flows likely with the Limpopo River likely to have higher river flows [3]	River flows increase from climate change scenarios under all RCPs, with land-use considerations showing the Limpopo River will likely have higher river flows [3]	Increased flow variability, potential for more floods/droughts, impact on agriculture/energy sectors and hence the livelihood of people, need for coordination

5.2. Remote Sensing Applications for Hydrological Monitoring

To complement these advancements in climate modeling and address persistent uncertainties in hydrological projections and data scarcity, remote sensing applications have emerged as a cost-effective and increasingly indispensable tool for monitoring terrestrial water cycles and supporting hydrological investigations across Africa [84,85]. With traditional, ground-based monitoring networks being sparse and often inadequate [19], 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 [42,55,84,86–88].

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 [8,35,84,89–91]. Innovative multi-sensor fusion approaches have enabled the integration of datasets from different satellite missions to produce high-resolution, comprehensive monitoring products [79,88]. 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 [84,89,92]. Other notable advancements leveraging remote sensing data include the high-resolution discharge datasets, VegDischarge, which covers over 64,000 segmented river reaches across Africa [93]; this 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 [4,8,29,79,94]. These integrated approaches will improve the accuracy of hydro-meteorological forecasts and 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

Building on these advancements in hydrological monitoring and forecasting, 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 [7,8,25]. 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 between vegetation, atmosphere, and hydrology [94]. 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 in a changing climate.

Moreover, proactive adaptation measures are essential to mitigate climate change impacts on water resources across African basins. These measures must address both gradual shifts in mean hydrological conditions and the growing variability and intensity of extremes such as droughts and floods. Although multi-model ensembles and rigorous bias-correction techniques have advanced our understanding of potential future hydrological changes, considerable uncertainty remains at local scales [8,95]. Consequently, developing and implementing robust early-warning systems for droughts and floods is a top adaptation priority, as these systems protect lives, safeguard infrastructure, and underpin sustainable water management in highly vulnerable regions [44].

Also, nature-based solutions, particularly Ecosystem-based Adaptation (EbA), offer promising pathways to climate resilience by leveraging ecological processes to mitigate water stress. For example, Figure 4 illustrates how EbA can provide multiple benefits, including mitigation, adaptation responses, and enhanced resilience, while simultaneously addressing climate change pressures and other environmental drivers. For instance, green infrastructure, including green roofs, urban parks, wetlands, and forests, can improve stormwater management, reduce flood risk, and enhance groundwater recharge [75]. Beyond urban settings, restoring natural ecosystems such as mangroves, salt marshes, and coral reefs also offers cost-effective coastal protection and supports biodiversity. Similarly, riverbank re-greening presents a viable alternative to conventional river training methods for reducing flood risks. In many situations, hybrid "green-gray" approaches, which combine engineered and nature-based solutions, offer the versatility needed to bolster overall water resilience. Furthermore, cooperative water management in transboundary basins is essential for achieving sustainable development, reducing conflict risks, and enhancing regional resilience [73]. 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.

Figure 4. Ecosystem-based adaptation (EbA) framework showing the interconnections between climate change, ecosystems, ecosystem services, and human adaptive capacity. This illustrates how EbA can provide multiple benefits, including mitigation, adaptation responses, and enhanced resilience, while addressing both climate change pressures and other environmental drivers. This framework is particularly relevant for African contexts where nature-based solutions can provide cost-effective alternatives to traditional infrastructure. Source: IUCN Ecosystem-based Adaptation Guidelines [96].

6. Future Directions in African Hydrology Research

Forging a resilient water future for Africa demands a strategic and multi-faceted research agenda, building upon the synthesis of current knowledge and identified gaps. Several priority areas emerge to guide future efforts towards enhanced water security and sustainable management.

Firstly, advancing the scientific understanding and predictive capabilities of African hydrological systems depends on developing integrated, multi-scale models that seamlessly couple atmospheric circulation shifts with thermodynamic processes, such as moisture-holding capacity and evapotranspiration rates, while resolving the complex, non-linear feedback among vegetation cover, soil moisture, and the atmosphere. At the same time, strengthening hydrometeorological monitoring networks is essential. For example, expanding ground-based and satellite observations improves spatial and temporal coverage, and building institutional capacity ensures that data collection, sharing, and interoperability become routine. By harnessing advanced analytics, including machine-learning algorithms for data assimilation and pattern recognition, we can transform these observations and model outputs into operational early-warning systems that accurately forecast droughts and floods in real time. Further research should also explore the potential of citizen science to augment traditional data collection, fostering community engagement and local knowledge integration.

Secondly, effective water management demands robust governance and policy frameworks. Future research must focus on developing equitable and effective transboundary governance frameworks for shared water resources. This includes exploring robust institutional mechanisms for data sharing, joint planning, and conflict resolution that acknowledge diverse stakeholder interests. Crucially, these frameworks should explicitly integrate the water–energy–food nexus into adaptation strategies to enhance overall system resilience across sectors. Moreover, effective implementation and impact assessment of water policies at local to national scales should consider socio-economic equity and vulnerability.

Thirdly, strengthening the resilience of African hydrological systems requires both rigorous evaluation of ecosystem-based adaptations and the advancement of climate-resilient infrastructure. Field and modelling studies should quantify how interventions, such as wetland restoration, reforestation, and managed aquifer recharge, modify key hydrological fluxes (runoff, infiltration, evapotranspiration) across diverse climatic and land-use contexts and translate these findings into site-specific implementation guidelines. Concurrently, engineering research must develop low-cost, low-carbon, modular infrastructure, ranging from permeable pavements and decentralized rainwater harvesting to adaptive flood barriers, and assess each option's cost-effectiveness, durability, and maintenance requirements.

Finally, a truly resilient water future requires dedicated socio-economic and interdisciplinary research. This includes in-depth studies on the socio-economic impacts of water scarcity and extremes, detailed vulnerability assessments across different communities, and research into mechanisms for the equitable distribution of water resources. Fostering sustained interdisciplinary collaboration across natural sciences, social sciences, engineering, and policy, alongside significant investment in capacity building and education for the next generation of African hydrologists and water managers, are critical cross-cutting themes that will underpin all future advancements.

7. Conclusions

This review demonstrates that African hydrology exhibits extraordinary complexity and sensitivity across various temporal scales, from contemporary observations to future projections. The continent's water systems display distinct threshold behaviors, non-linear responses, and asynchronous regional patterns that challenge simplistic climate–hydrology paradigms. These characteristics demand sophisticated analytical tools and adaptive management strategies to address water security sustainably amid rapid environmental changes. The spatial variability of these characteristics reinforces the need for locally tailored management strategies rather than uniform, continent-wide approaches. Moreover, this analysis reveals that successful adaptation requires integrated approaches that combine advanced monitoring technologies, ecosystem-based solutions, and effective governance frameworks. Also, 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 various basins. The synthesis presented here provides a foundation for evidence-based decision-making in water resource management and climate adaptation across Africa's diverse hydrological systems.

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Abbreviations

The following abbreviations are used in this manuscript:

RCP	Representative Concentration Pathway
ESM	Earth System Models
LULC	Land-use Land-cover
DEM	Digital Elevation Model
EbA	Ecosystem-based Adaptation
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 Change
ET	Evapotranspiration
LULCC	Land-use Land-cover change
CORDEX	Coordinated Regional Climate Downscaling Experiment
GRACE	Gravity Recovery and Climate Experiment
bSOA	Biogenic secondary organic aerosols
HydroSHEDS	Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales

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