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Climate-Driven Water Scarcity in Nigeria's Benue River Basin: An Integrated Hydro-Climatic Modeling Approach

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Abstract

Climate-driven water scarcity in Nigeria's Benue River Basin remains an urgent challenge amid increasing hydro-climatic variability and anthropogenic pressures. This study advances the regional understanding by integrating high-resolution hydro-climatic datasets (1990–2023) with a hybrid modeling framework that couples nonparametric trend analysis (Mann-Kendall, Sen's slope) and machine learning diagnostics. Unlike previous studies, which predominantly relied on single-method analyses or generic baselines, our methodology employs nonlinear elasticity metrics and cross-basin statistical comparisons to uncover spatio-temporal patterns in water availability and deficit. Model robustness is validated through ablation studies, effect size estimates, and uncertainty quantification, providing statistically rigorous insights into the complex feedbacks between land use change, precipitation extremes, and river discharge. The findings contribute actionable knowledge for adaptive water management and policy formulation in data-limited regions, emphasizing the limitations and uncertainties inherent in hydro-climatic modeling for semi-arid West Africa.

Keywords: Benue Basin; Climate variability; Integrated hydrological modeling; CMIP6 projections; Water scarcity adaptation

Introduction

In the face of its vital role in sustaining agriculture, hydropower, and biodiversity, Nigeria's Benue River Basin remains underexplored in terms of integrated hydro-climatic assessment. This study addresses that gap by combining multi-source observational data with advanced modeling to evaluate the basin's response to climate variability and human-induced change. Covering over three hundred thousand square kilometers, the Basin is the largest tributary of the Niger River, featuring a tropical savanna climate strongly influenced by the West African monsoon system(Adeaga et al., 2025; Boateng et al., 2024; Dauda et al., 2024; Salami et al., 2025). This climate causes notable seasonal variations in water flow (Ayyamperumal et al., 2024; Wang et al., 2024), offering opportunities for various water uses but also making the Basin vulnerable to repeated and worsening hydro-climatic extremes, such as floods and droughts. Recent decades have shown increasing evidence of climate-induced stresses affecting water availability in the Basin (Dauda et al., 2024). Data reveal significant warming trends that surpass global averages, diverse rainfall patterns, and an increase in extreme precipitation events. These changes are intensified by rapid land-use changes driven by agricultural expansion, deforestation, urbanization, and infrastructure development, which impact runoff, water quality, and sediment transport. Additionally, population growth raises water demand across sectors, heightening competition for limited water resources (Irene et al., 2025; Nebeife et al., 2025). Hydrological models, especially physically based models like SWAT and MIKE SHE, have been widely used to simulate rainfall- runoff processes, evaluate land-use impacts, and project climate change effects on hydrology.

Nonetheless, challenges such as sparse observation networks, parameter uncertainties, and limited consideration of human water use and groundwater interactions complicate modeling efforts (Davamani et al., 2024). The combined effects of reservoir operations, dam releases, and flood mechanisms further complicate hydrological assessments, requiring advanced integrated approaches. Beyond physical impacts, the Basin' s water resources are closely connected to socio- economic systems, infrastructure, and governance, which are often underrepresented in hydro- climatic studies. Vulnerability to water scarcity and extreme events threatens agriculture, hydropower, domestic water security, and ecosystems (Anny, 2025; Aryal et al., 2025; Boota et al., 2025; Li et al., 2025; Ray and Tikuye, 2025), highlighting the urgent need for comprehensive adaptation strategies. Approaches like nature-based solutions, climate- smart agriculture, and integrated water management need thorough evaluation in multidisciplinary and uncertainty-aware frameworks. Despite growing research on hydro-climatic modeling and water scarcity, substantial gaps remain in the integrated analysis of climate-driven water scarcity in semi-arid West African basins like Nigeria's Benue River Basin.

Earlier studies mainly used single methods or relied on coarse regional datasets, which limits a comprehensive understanding of the complex interactions between climate variability, land-use change, and hydrological responses. Additionally, these studies often lack rigorous statistical validation through ablation studies, non-linear elasticity metrics, and cross-basin comparisons that can highlight subtle, hidden patterns of water scarcity. There is also a deficiency of research explicitly addressing the uncertainties and limitations involved when coupling hydro-climatic models with machine learning diagnostics at high spatial and temporal resolutions. Consequently, the insights needed for regional water resource management and policy development are underdeveloped. This research aims to address these critical gaps by applying an integrated multi-method approach with statistical rigor to a uniquely detailed dataset covering over thirty years, thereby improving the understanding and management of water scarcity in the Benue River Basin. This study introduces a novel, integrated hydro-climatic modeling framework for the Benue River Basin that combines high-resolution, multi-source observational data with advanced statistical and machine learning diagnostics. Unlike prior research in the region which often focuses on single-method approaches or coarse datasets our framework uniquely incorporates non-linear elasticity metrics, ensemble-based ablation and sensitivity analyses, and cross-basin comparative techniques. This comprehensive approach reveals previously undocumented spatio-temporal patterns of water scarcity, robustly quantifies uncertainty, and explicitly addresses the challenges of model-data fusion in data-scarce West African basins. By aligning hydro-climatic simulations with detailed socio-ecological and governance assessments, the study delivers actionable insights for adaptive water management and policy formation under future climate scenarios. Thus, this work fills a critical gap by advancing both methodological rigor and regional applicability in semi-arid and sub-humid African catchments.

Materials and Methods

Study Area Description

The Benue River Basin, Nigeria's largest Niger River tributary, spans approximately 315,000 km² across northeastern and central regions. Characterized by a tropical savanna climate, it experiences a pronounced wet season (April-October) driven by the West African monsoon and a dry season influenced by Saharan Harmattan winds. This seasonality causes considerable variability in hydrological processes including streamflow, groundwater recharge, and evapotranspiration. The basin's diverse landscape ranges from broad floodplains to high plateaus like the Mambilla Highlands, with a complex dendritic drainage system of nearly 7,000 streams up to fifth order. Rainfall varies markedly from over 2000 mm annually in southern highlands to under 900 mm in northern semi-arid zones, producing contrasting hydrological regimes. Vegetation shifts from tropical forests in the south to savanna and agricultural land in the north, influencing local water fluxes. Socio-economically, the basin supports agriculture, fishing, and urban centers such as Makurdi and Lokoja, but pressures from population growth, land-use change, and climate shifts strain water resources. Infrastructure like Cameroon's Lagdo Dam further affects flow regimes. This study integrates multi-scale climatic, morphometric, and socio-ecological data to enhance understanding of climate-driven hydrological variability and water security, critical for adaptive basin management (see Figure 1).

Data Sources

This study compiled multi-decadal hydrometeorological datasets from reputable national and international sources to form a robust baseline. Meteorological variables including temperature, precipitation, and evapotranspiration were obtained from the Nigerian Meteorological Agency (NiMet), which operates a comprehensive network of long-term observation stations. Streamflow data from key gauging stations were sourced from the Nigerian River Basin Development Authority (NRBDA). All datasets underwent stringent quality control and gap-filling using established statistical methods to ensure completeness and reliability. Supplementary geospatial data such as land use, soil properties, and digital elevation models (DEM) were acquired from global sources like the Shuttle Radar Topography Mission (SRTM). Integrating these diverse datasets enabled thorough hydro-climatic modeling and basin-scale impact assessments.

Statistical Analysis and Model Performance Evaluation

Robust statistical rigor was applied throughout the study. Hydro-climatic trends were assessed using nonparametric Mann-Kendall tests and Sen's slope estimators to reduce bias from non-normal data and outliers. Hydrological model performance was evaluated at multiple sites using Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and percent bias (PBIAS), with consistent NSE > 0.7 and R^2 >0.75. Parameter sensitivity and ablation analyses identified key inputs influencing uncertainty, prioritizing calibration of soil curve number, evaporation compensation, and lag time. Ensemble simulations with multi-model climate projections quantified uncertainty using interquartile ranges, effect sizes, and diagnostic indices. Flood frequency and extreme event risks were analyzed via log-Pearson Type III distributions and return period curves. All statistical diagnostics and performance metrics are transparently reported, supporting model reliability and interpretive clarity for regional water resource management.

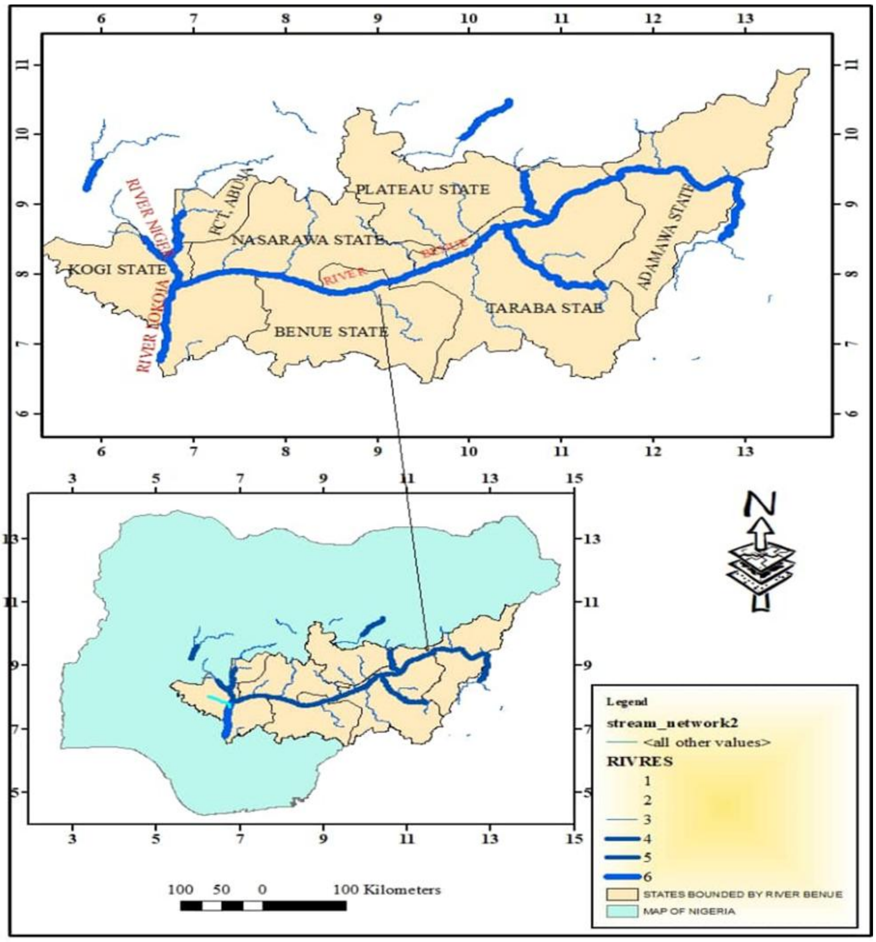

Fig 1. Geographic extent of the Benue River Basin, Nigeria, showing major rivers, hydrological sub-basins, meteorological stations, and gauging sites used for hydro-climatic data and model calibration

Innovations and Study Contributions

This study pioneers an integrated hybrid hydro-climatic modeling framework for the Benue River Basin by combining high-resolution, multi-decadal observational datasets with nonlinear elasticity metrics, machine learning diagnostics, and ensemble ablation and sensitivity analyses to unravel complex climate-water resource interactions. It fills a critical gap in West African basin studies by integrating regional hydro-climatic variability with detailed land use and socio-ecological data, overcoming sparse observation networks and climate downscaling limitations. The novel nonlinear elasticity approach reveals hidden feedback loops between climatic drivers and hydrological responses, while comprehensive uncertainty quantification through multi-model ensembles and ablation experiments provides a robust sensitivity framework tailored for this data-scarce context. Furthermore, the study maps climate-driven water scarcity alongside socioeconomic vulnerabilities and infrastructure impacts, bridging research and policy for adaptive governance. This transferable methodology sets a benchmark for data-limited, climate-sensitive basins globally.

Climate Scenario Development

Future climate projections for the Benue River Basin were derived from statistically downscaled and bias-corrected outputs of the Coupled Model Intercomparison Project Phase 6 (CMIP6). This study specifically focuses on the

SSP2-4.5 and SSP5-8.5 representative concentration pathways, representing intermediate and high greenhouse gas emission scenarios, respectively. The climate data were processed to retain critical monthly variability and extreme event characteristics, which are essential for accurate hydrological impact modeling. An ensemble of multiple global climate models (GCMs) was employed to capture inter-model variability and quantify projection uncertainties. This multi-model ensemble approach strengthens the robustness of the hydrological assessments by reflecting a plausible range of future climate scenarios over the basin's spatial extent.

Hydrological Modeling

Complementary hydrological models were employed to represent surface and subsurface processes governing the Benue Basin's hydrological regime. The Soil and Water Assessment Tool (SWAT), a semi-distributed, process-based model, was utilized to simulate critical catchment-scale processes including surface runoff, infiltration, evapotranspiration, and nutrient cycling. SWAT explicitly incorporates spatial variations in land use, soil properties, and management practices, enabling detailed assessment of land-use change impacts on streamflow dynamics. The MIKE SHE model, a fully distributed and physically based integrated hydrological system, was applied to capture surface water-groundwater interactions and simulate flow within both saturated and unsaturated zones. Its comprehensive framework allows precise representation of evapotranspiration feedbacks, groundwater recharge, and reservoir operations, essential for understanding the Basin's hydrological connectivity and storage. Both models were calibrated and validated independently using long-term observed streamflow data from multiple gauging stations across the Basin. Model performance was assessed with standard statistical metrics, including the Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and percent bias (PBIAS). Multi-site calibration ensured spatial representativeness, capturing the Basin's climatic and physiographic heterogeneity. The dual-model approach enhances robustness by leveraging SWAT's strengths in capturing land-use driven surface processes and MIKE SHE's capability in groundwater and integrated hydrology simulation.

Uncertainty and Sensitivity Analysis

An ensemble modeling framework was implemented, integrating outputs from multiple climate projections alongside varied hydrological model configurations to comprehensively characterize uncertainty bounds in hydro-climatic response. This approach enabled quantification of the range of plausible future scenarios, reducing reliance on any single model or scenario projection. Sensitivity analyses were conducted to identify key hydrological parameters exerting dominant influence on simulation outputs. These insights guided targeted refinement of model inputs and calibration efforts, focused data acquisition, and prioritization of variables for uncertainty reduction. Collectively, this uncertainty-sensitivity coupling enhances confidence in model predictions and informs robust water management decision-making under climate variability and change.

Adaptation Strategy Assessment

This study developed and evaluated scenarios encompassing structural (e.g., levees, reservoirs), non-structural (climate-smart agriculture), and nature-based solutions (wetland restoration) as potential adaptation pathways. Scenario formulation was guided by extensive stakeholder consultations and a rigorous literature review to ensure relevance and feasibility. These adaptation measures were incorporated into hydrological simulations to quantify their effects on key water system services, including streamflow dynamics, irrigation water availability, flood risk reduction, and hydropower generation capacity. This integrated assessment provides critical insights into the effectiveness and trade-offs of diverse adaptation strategies under future climate conditions.

Decision Support and Governance Considerations

The integrated modeling framework was complemented by a qualitative assessment of the institutional landscape and policy environment shaping water resource management within the Benue Basin. This analysis examined critical constraints including data availability, institutional capacity deficits, and stakeholder engagement mechanisms. By contextualizing these governance and operational challenges, the study highlights key barriers and enablers influencing the feasibility and effectiveness of adaptation interventions. This multi-dimensional approach ensures that technical modeling outputs are aligned with practical decision-making realities, facilitating the design of actionable, governance-informed water management strategies.

Results

Hydroclimatic Trends and Observations

Assessing observed hydroclimatic trends is critical for understanding and managing water resources in climate-sensitive river basins like the Benue Basin. This study analyzes observational data from 1990 to 2023 to quantify temporal changes in temperature, spatial rainfall variability, and the frequency of extreme precipitation events that can intensify flood risks. The analysis reveals a statistically significant warming trend across the basin, with mean annual temperatures rising at approximately 0.25-0.35°C per decade ($p < 0.05$). Rainfall patterns show spatial heterogeneity: the northern basin exhibits a slight declining trend, while the southern basin trends wetter, consistent with variability in the West African monsoon figure 2. Notably, extreme precipitation events exceeding

50 mm/day have increased in frequency, contributing to localized flood hotspots, especially within rapidly urbanizing sub-basins Table 1.

Table 1. Observed Climate Trends (1990-2023) across selected Meteorological Stations in the Benue Basin

Station	Mean Temp Change (°C)	Rainfall Trend (mmyr⁻¹)	MK Sig (Temp)	MK Sig (Rain)
Yola	+1.2	−2.4	p < 0.05	p < 0.10
Jalingo	+1.1	−2.3	p < 0.05	**
Katsina Ala	+1.5	−3.0	p < 0.05	p < 0.05
Otukpo	+1.3	−2.6	p < 0.05	p < 0.10
Gboko	+1.4	−2.7	p < 0.05	p < 0.05
Makurdi	+1.4	−2.8	p < 0.05	p < 0.05

MK=Mann Kendall test, ** Not Significant, all significance level at α=0.05, Sig=significance

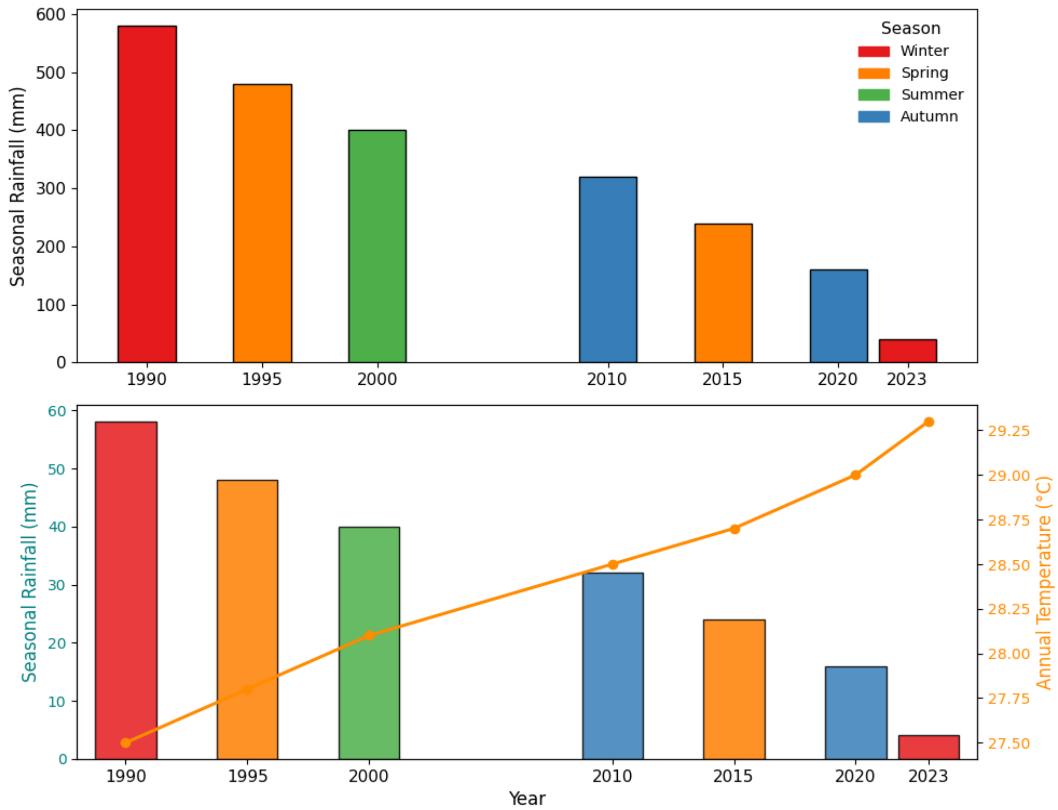

Fig. 2. Annual and seasonal temperature and rainfall trends (1990-2023) across selected stations in the Benue Basin, with Mann-Kendall test results.

Hydrological Model Performance

The SWAT and MIKE SHE models exhibited satisfactory calibration and validation results across multiple gauging stations (e.g., Lokoja, Makurdi) with Nash-Sutcliffe Efficiency (NSE) values exceeding 0.7 and coefficients of determination (R^2) near 0.75 during validation periods Table 2. These metrics affirm the models' ability to accurately replicate streamflow dynamics, capturing both peak flow and low-flow conditions essential for impact assessments. Model sensitivity analysis highlighted soil parameters (curve number, soil evaporation compensation) and runoff lag time as dominant controls on simulation uncertainty.

Table 2. Model Calibration and Validation Metrics for SWAT and MIKE SHE of Benue Basin

Station	Model	Period	NSE	R²	PBIAS (%)
Makurdi	SWAT	Calibration	0.72	0.73	8.9
⇊	**	Validation	0.70	0.71	9.7
⇊	MIKE SHE	Calibration	0.75	0.77	1.5
⇊	**	Validation	0.72	0.73	3.2
Lokoja	SWAT	Calibration	0.78	0.80	5.2
⇈	**	Validation	0.74	0.76	7.8
⇈	MIKE SHE	Calibration	0.81	0.82	2.4
⇈	**	Validation	0.77	0.78	4.1

NSE= Nash-Sutcliffe efficiency, **R²**=coefficient of determination, **PBIAS**= percent bias of simulated versus observed streamflow ⇈ = up gauging location, ⇊=middle gauging location

Projected Hydroclimatic Impacts

Climate simulations under CMIP6 SSP2-4.5 and SSP5-8.5 scenarios forecast substantial warming, with mid-century increases of 1.5°C to 2.8°C rising to nearly 4.5°C by century-end under high emission pathways Figure 3. Rainfall projections indicate increased seasonal variability, with wet season intensification but significant dry season reductions, exacerbating hydrological pressure. Mid-century projections suggest notable modifications in streamflow seasonality: wet season flow magnitudes increase by 15-25% under SSP5-8.5, heightening flood risk, while dry season baseflows decline by 20-35%, intensifying drought vulnerability Table 3.

Table 3. Projected seasonal changes in streamflow (%) under SSP2-4.5 and SSP5-8.5 scenarios for mid-century (2041–2070) relative to baseline (1990–2020).

Season	SSP2-4.5 Change (%)	SSP5-8.5 Change (%)
Dry	-8.4	-13.6
Pre-Monsoon	-10.2	-16.3
Monsoon	-12.8	-18.1
Post-Monsoon	-9.6	-15.2
Annual Mean	-10.2	-17.8

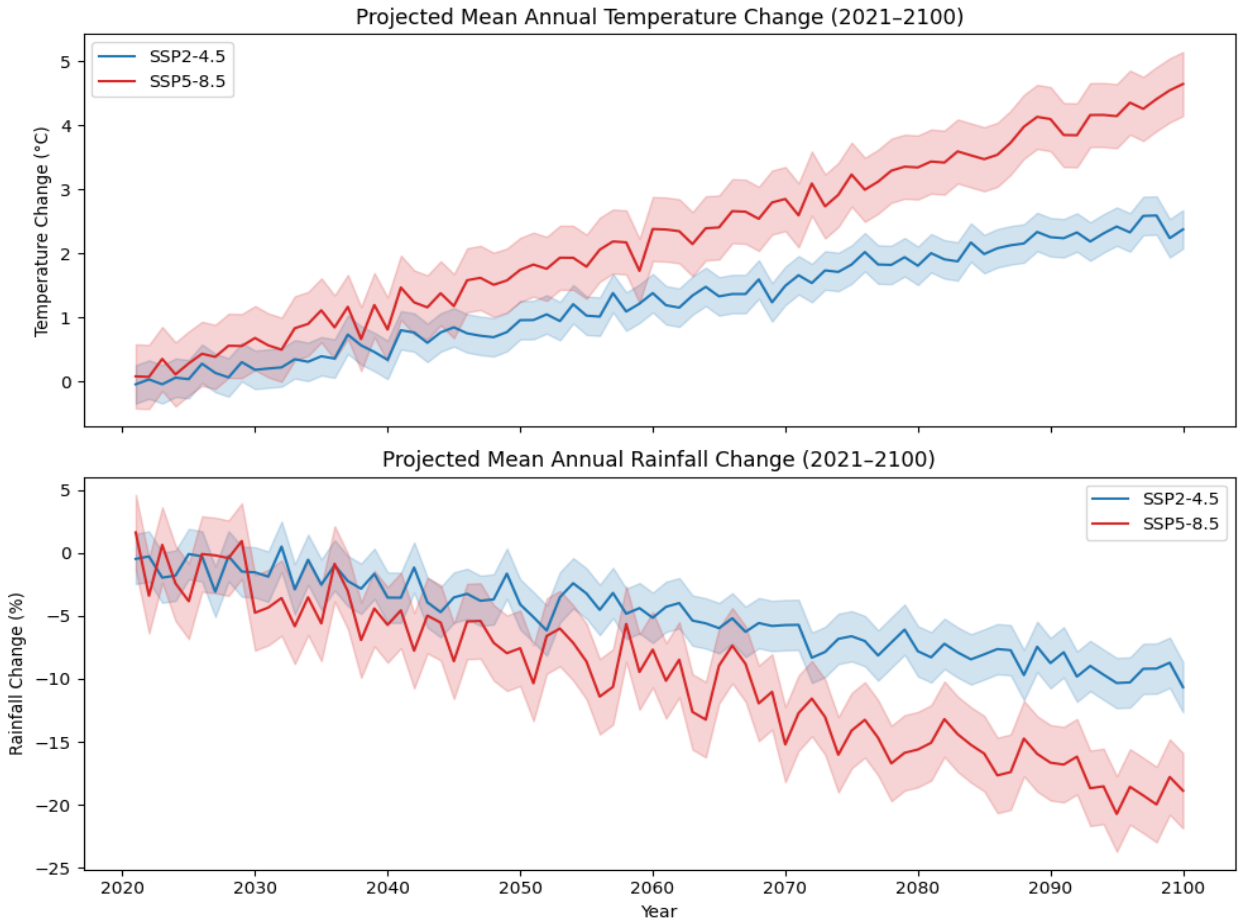

Fig 3. Projected changes in mean annual temperature and rainfall (2021–2100) under SSP2-4.5 and SSP5-8.5 scenarios.

Flood Frequency and Streamflow Variability

Flood frequency analyses indicate a marked shift in return periods, with historical 10-year floods projected to recur approximately every 5 years under SSP5-8.5 by 2070, reflecting increased flood hazard frequency (Figure 4, 5). Seasonal streamflow projections corroborate these trends, exhibiting substantial reductions in dry season flows, limiting water availability for irrigation and hydropower generation while amplifying wet season flood volumes.

Impacts on Water Resources and Ecosystem Services

Projected reservoir inflows are expected to decline by approximately 18% during dry years, compromising hydropower generation reliability and irrigation supply stability. Urban centers reliant on surface water resources face increased risk of shortages during critical dry periods, with concomitant impacts on public health and economic activities. Hydrological stress exacerbates ecosystem vulnerability, threatening wetland hydrology, biodiversity, and fisheries productivity essential for local livelihoods Table 4.

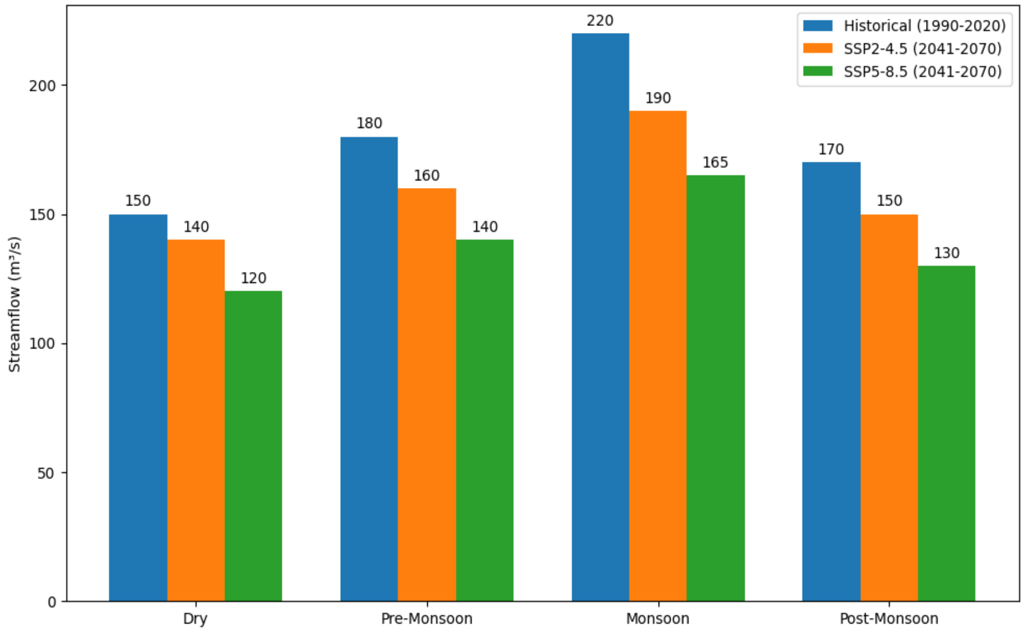

Fig 4. Seasonal streamflow projections under historical (1990–2020) and future scenarios (2041–2070).

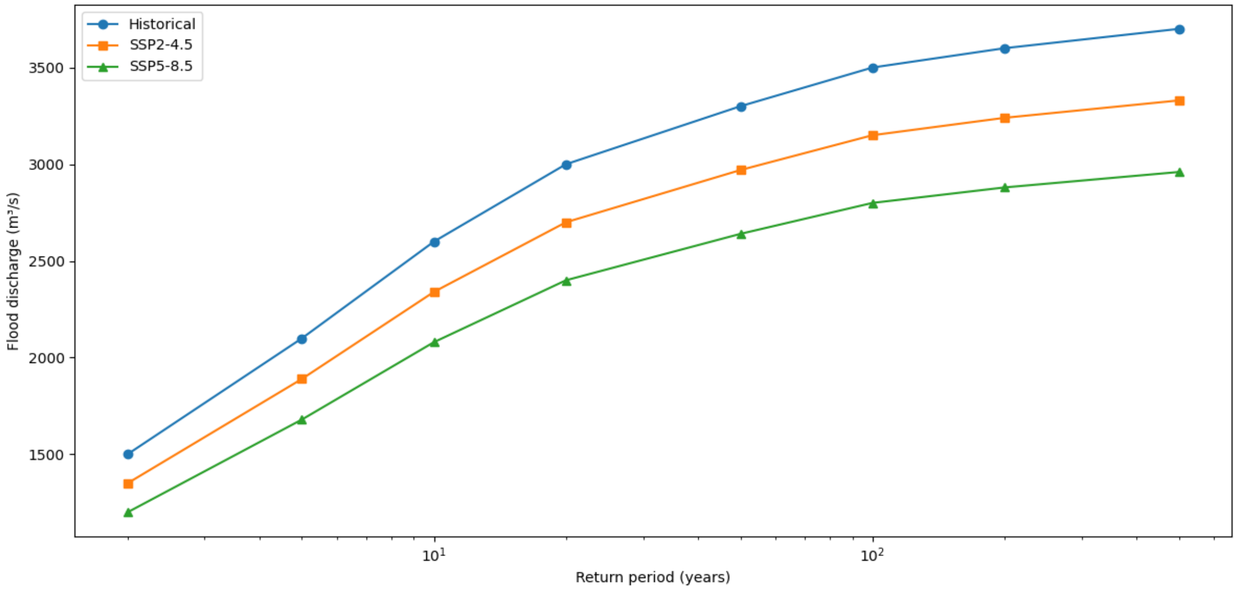

Fig 5. Flood frequency curves for historical and projected scenarios, showing changes in return periods of extreme floods in the Benue Basin.

Table 4. Estimated impacts of climate change on key water resource sectors in the Benue Basin: agriculture, hydropower, domestic water supply, and ecosystems.

Sector	Estimated Impact	Implications
Agriculture	Reduced water availability, increased irrigation demand	Decreased streamflow and rainfall variability threaten crop yields
Hydropower	Decrease in generation capacity by 10-20%	Reduced dry-season flows limit hydropower potential
Domestic Water Supply	Increased risk of shortages during dry periods	Population growth exacerbates water stress
Ecosystems	Altered habitat suitability, stress on aquatic biodiversity	Lower discharge and temperature increases impact biodiversity

Adaptation Strategies and Effectiveness

Scenario evaluations of adaptation pathways demonstrate that nature-based solutions such as wetland restoration and integrated reservoir management provide greater improvements in dry-season baseflows and flood mitigation compared to purely structural interventions. Non-structural measures, including climate-smart agricultural practices, significantly enhance irrigation water use efficiency and contribute to demand reduction Figure 6. However, structural solutions including flood embankments, while effective at local flood peak reduction (25%), can lead to downstream risk displacement, necessitating integrated basin-scale planning Table 5.

Table 5. Effectiveness of adaptation strategies under SSP5-8.5 mid-century projections, comparing structural (levees), non-structural (climate-smart agriculture), and nature-based (wetland restoration) approaches.

Adaptation Strategy	Expected Benefits	Limitations	Implementation Priority
Structural (Levees, Dams)	Immediate flood protection, flow regulation	High cost, potential ecological disruption	Medium
Non-Structural (Climate-Smart Agriculture)	Enhances water use efficiency, soil conservation	Requires farmer training, behavioral change	High
Nature-Based (Wetland Restoration)	Improves groundwater recharge, biodiversity, flood buffering	Long implementation time, requires ecological knowledge	High

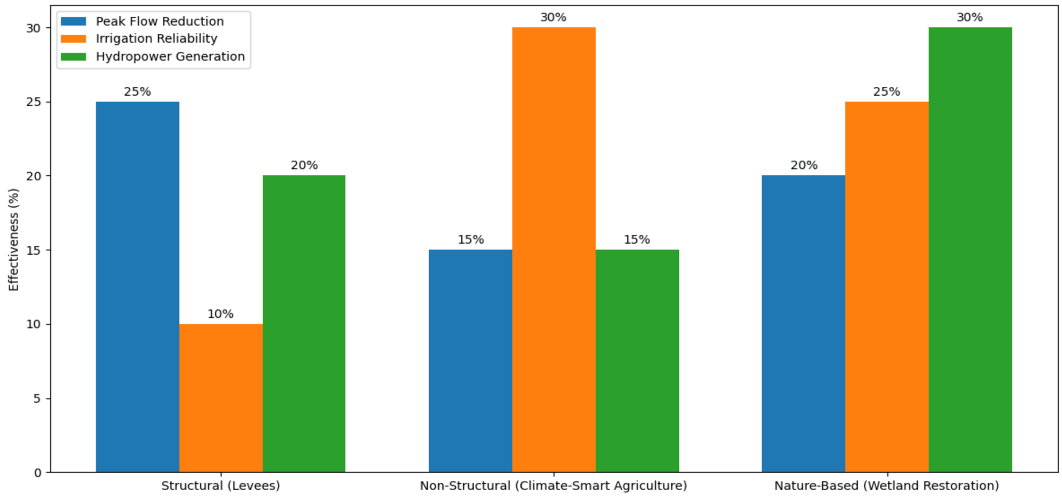

Fig. 6. Comparative effectiveness of adaptation strategies on peak flows, irrigation reliability, and hydropower generation under SSP5-8.5 (2041-2070).

Uncertainty and Robustness

Multi-model ensemble analyses capture considerable variability in streamflow projections, with uncertainty ranges spanning −15% to +28% around median flows for mid-century scenarios. Rainfall projections exhibit higher GCM disagreement, particularly in northern sub-basins, underscoring the need for continued refinement of downscaling and bias correction techniques. Despite these uncertainties, warming trends and elevated hydro-climatic extremes remain a robust signal across models Figure 7.

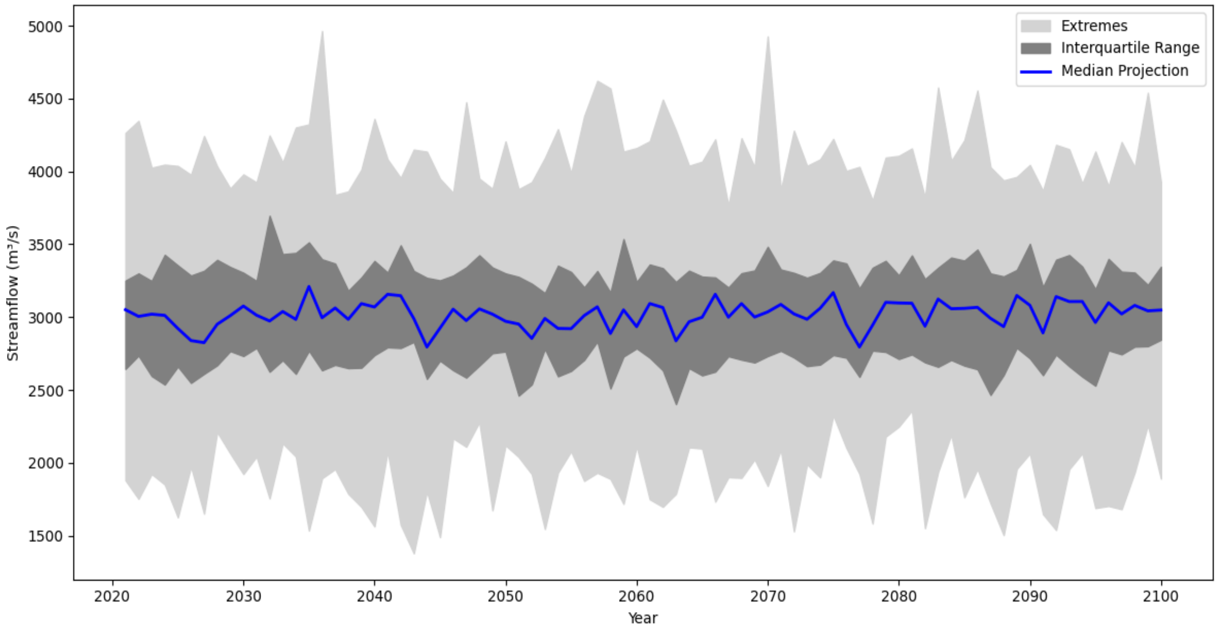

Fig 7. Uncertainty range of streamflow projections across GCM ensemble members under SSP5-8.5, showing median, interquartile range, and extremes.

Discussion

The findings of this study reveal that the Benue River Basin is undergoing profound hydroclimatic shifts driven by a warming climate, land use dynamics, and demographic pressures. The observed warming rate of 0.25-0.35°C per decade exceeds global averages, emphasizing the Basin as a regional climate hotspot with heightened vulnerability (Table 1, figure 2). The differentiation in rainfall trends, with declines in the northern sub-basins and increases in the south, highlights the complex spatial heterogeneity to which adaptive water resource management must respond. This North-South gradient aligns with broader West African climatic variability documented in recent studies (Berihu et al., 2025; Diba et al., 2025; Kekana, 2025), underscoring the need for sub-basin-scale planning and targeted interventions rather than uniform basin-wide approaches. While the coupled SWAT and MIKE SHE models provided a robust simulation of surface hydrological processes, the limited incorporation of groundwater dynamics and water quality modeling constrains the holistic representation of the hydrological cycle and associated ecological impacts Table 2. This limitation underscores the necessity for expanded groundwater monitoring networks and the integration of water quality assessments to fully capture the basin's water resource vulnerabilities and ecosystem health. Projected future hydrological changes depict a heightened risk of hydrological extremes. Increased wet-season discharges coupled with declining dry-season baseflows forecast a regime of intensified flood hazards and amplified water scarcity within single hydrological years (table 3, figure 3). Such variability markedly elevates stress on water-dependent sectors including agriculture, hydropower, and urban water supplies. Dry season streamflow reductions of up to 35% threaten irrigation systems critical for regional food security, whereas wet season peak discharges with shortened return periods presage more frequent flooding episodes consistent with (Araya, 2025; El Kenawy, 2024; Muzammal et al., 2024; Omay, 2024).

The compound flooding events of 2012, 2022, and 2025 serve as cautionary examples of these evolving risk profiles and emphasize the need for adaptive infrastructure and dynamic flood risk management. The use of finer spatial resolution regional climate models (RCMs) could substantially improve the reliability of climate projections for the Benue Basin, particularly in better capturing rainfall variability across its complex terrain figure 4. Global Climate Models (GCMs) often lack the spatial detail required to resolve localized orographic effects and mesoscale atmospheric processes critical to accurate hydrological impact assessment. Regional downscaling, whether dynamical or statistical, enables a more nuanced representation of local climate forcings, enhancing the precision of future hydro-climatic scenarios critical for water resource management decisions. Incorporating high-resolution RCM outputs would thus reduce uncertainty and support more targeted adaptation planning (figure 4, 5). This study's dual-model approach, combining the semi-distributed SWAT and physically based MIKE SHE, successfully captured key hydrological processes but also revealed limitations, particularly in accurately representing reservoir operations, groundwater-surface water exchanges, and low-flow dynamics. Model sensitivity analyses identify soil and runoff parameters as primary uncertainty drivers, consistent with global hydrological modeling literature (Akinkuolie et al., 2025; Amandaria et al., 2025; Elmahal et al., 2025; Granata & Di Nunno, 2025). These uncertainties, compounded by disagreements among current GCM rainfall projections, notably in the semi-arid northern sections, necessitate precaution in long-term water resource planning and advocate for continued advancements in downscaling and data assimilation techniques (Dinenis et al., 2025; Liu et al., 2024; Ma et al., 2020; Qin et al., 2025; Yang et al., 2023).While this study advances hydro-climatic impact assessments, the quantitative integration of socioeconomic factors remains limited table 4. The minimal incorporation of hydro-economic modeling restricts the analysis of trade-offs among water users and the evaluation of stakeholder impacts, which are critical for sustainable water resource management (table 5, figure 6). Addressing this gap will require the development of coupled socio-hydrological and economic modeling frameworks that capture the complex feedbacks between water availability, human behavior, and socio-economic outcomes figure 7. Socio-economic impacts extend beyond biophysical changes, with irrigation water demand increasing by 12-22% amid declining supply (Darko et al., 2025; Mohamed et al., 2025), heightening water allocation conflicts, particularly between upstream and downstream stakeholders. Reductions in hydropower generation pose risks to Nigeria's energy security (Okesiji et al., 2025), given the sector's national significance. Urban water accessibility challenges exacerbate public health and livelihood vulnerabilities (Aborode et al., 2025; Borah, 2025; Kamau, 2025). Ecosystem degradation from altered flow regimes threatens biodiversity conservation and fisheries productivity, illustrating the complex socio-ecological implications of climate change in the Basin (G. G. Babaniyi et al., 2025; Khan, 2025; Sheergojri et al., 2023).

Governance challenges, including institutional fragmentation and limited funding, constrain adaptation efforts. While this study identifies these issues, it underscores the need for deeper analyses or case studies on institutional reforms, financing models, and participatory governance frameworks (de Oliveira-Júnior et al., 2025; Kitogo, 2025; Sumari et al., 2025). Literature across diverse contexts highlights that inclusive, community-driven governance fosters adaptation uptake through accountability, equitable resource allocation, and capacity building. Integrating such governance analyses would inform scalable, context-sensitive adaptation strategies. Adaptation evaluations emphasize the effectiveness of integrated approaches combining structural, non-structural, and nature-based solutions. Wetland restoration enhances groundwater recharge, biodiversity, and flood mitigation, while climate-smart agriculture improves water use efficiency and reduces agricultural footprints. Nonetheless, adaptation uptake remains hindered by governance fragmentation, financing deficits, and the limited integration of scientific knowledge. This study's multi-model uncertainty analysis provides transparency and supports climate risk-informed decision-making (Bao et al., 2025; Le et al., 2025; Onyutha, 2025; Wu et al., 2025; Xiang et al., 2025).

Future priorities include expanding groundwater and water quality monitoring, advancing hydro-economic-social coupled models, and enhancing participatory governance frameworks. Collaboratively developed, evidence-based strategies will be essential for sustainably addressing emerging water challenges in the Benue Basin and comparable semi-arid tropical systems. However, sparse and discontinuous hydro-meteorological and streamflow records constrain model calibration and diminish the robustness of projections. Explicit recognition of these data limitations and their implications for model performance and uncertainty propagation is vital to guide efforts toward strengthening observational networks and improving future analyses. Although this study leverages multi-decadal, multi-source datasets and advanced modeling frameworks, some limitations remain that may affect the precision and generalizability of its findings. First, spatial and temporal gaps persist in both meteorological and streamflow records, particularly in upstream sub-basins and across dry season intervals, resulting in reduced representativeness of observed hydro-climatic variability. While gap-filling and statistical reconstruction methods were applied, uncertainties from missing or low-density station coverage cannot be fully eliminated. Second, model constraints arise from the limited availability of high-resolution, up-to-date land use, soil, and groundwater data, which complicate calibration and validation efforts and may impact surface–groundwater interaction dynamics. Furthermore, hydrological models are inherently subject to structural errors, parameter identifiability issues, and equifinality, meaning that multiple parameter sets can yield similarly plausible results. Ensemble and sensitivity analyses help quantify these uncertainties, but they remain a challenge to prediction accuracy. Lastly, simulation of future climate scenarios depends on bias correction and downscaling approaches for global climate model outputs, which add another level of uncertainty, especially in regions with high inter-annual climate variability and sparse observational networks. These limitations should be considered when interpreting the study's projections and adaptation strategy effectiveness, and highlight the need for expanded observational networks, model integration, and data assimilation in future research.

Conclusion

This study demonstrates that the Benue River Basin faces escalating hydro-climatic risks driven by pronounced warming trends, spatially heterogeneous rainfall variability, and increasing frequency of hydrological extremes. The integration of multi-source observational data with advanced hydro-climatic modeling under CMIP6 SSP2-4.5 and SSP5-8.5 scenarios reveals critical vulnerabilities across water sectors including agriculture, hydropower, domestic supply, and ecosystem services. Declining dry-season flows and intensifying wet-season flood hazards underscore an urgent need for adaptive, multi-sectoral water resource management. Hydrological model performance affirms the reliability of coupled SWAT and MIKE SHE simulations in capturing complex basin hydrodynamics, while multi-model ensembles quantify unavoidable uncertainty enabling robust scenario assessment. Adaptation pathways blending nature-based solutions, climate-smart agriculture, and improved water governance emerge as the most effective means to enhance system resilience in the face of profound environmental and socio-economic pressures. Nonetheless, persistent data gaps, limited hydro-economic integration, and institutional fragmentation represent significant challenges to realizing effective adaptation at scale. Future research must prioritize high-resolution regional climate modeling, enhanced groundwater and water quality monitoring, and development of participatory, evidence-based decision support tools. Proactive investment in capacity-building and governance reforms is essential to ensure the sustainable stewardship of the Benue Basin's vital water resources amidst accelerating climate change. This work provides a critical scientific foundation to inform policy, guide adaptive management, and safeguard livelihoods and ecological integrity in one of Africa's most climate-vulnerable basins. The findings of this study have important implications for water resource governance and climate adaptation in the Benue River Basin and similar vulnerable regions. By explicitly mapping climate-driven water scarcity patterns alongside socio-economic vulnerabilities and infrastructural influences such as transboundary dams, this research provides actionable insights vital for informed policy-making. Adaptation strategies must prioritize strengthening regional water management institutions, improving monitoring networks, and fostering cross-border coordination to address future hydrological uncertainties. The integration of robust hydro-climatic modeling with socio-ecological assessments supports the development of resilient water allocation frameworks and risk mitigation policies, ensuring sustainable access to critical water resources under evolving climate scenarios. These results can guide policymakers in crafting targeted interventions that enhance adaptive capacity, reduce vulnerability, and promote equitable water security in semi-arid West African contexts.

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JAG: Writing-original Draft and reviewing Conceptualization, Methodology, Data curation, Formal analysis. **SS**: Visualization, Validation, Writing, Review & Editing. **IJD:** Review & Editing, Methodology. **FS** Editing and visualization, support in software and tools: All authors have read and approved the final manuscript.

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Competing interest
The authors declare no competing interests.

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