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Hybrid Deep Learning and Trend Analysis for Rainfall and Discharge Forecasting under Hydro-Climatic Risks in Nigeria's Benue Basin

John Ayuba Godwin[1], Shruti Singh[1], Ishaku Joshua Dibal[1], Rajesh Kumar[2], Jagvir Singh[3]

[1]Department of Physics and Environmental Sciences, School of Basic Sciences and Research, Sharda University, Greater Noida, Uttar Pradesh, India
[2]Department of Physics and Environmental Science, School of Earth Sciences, Central University of Rajasthan (CURAJ), NH8, Bandar Sindri, Ajmer, Rajasthan 305817, India
[3]Ministry of Earth Sciences, Government of India, Prithvi Bhawan, opposite India Habitat, Centre Lodhi Road, New Delhi 110001, India
*Correspondence for materials should be addressed to JAG (email: 2023811233.john@dr.sharda.ac.in)

Abstract
Hydro-climatic variability poses significant risks to water resources, agriculture, and livelihoods in West Africa, where river basins remain highly vulnerable to climate change and data scarcity. This study investigates long-term rainfall and discharge trends in Nigeria's Benue River Basin (1990–2023) and develops a hybrid deep learning framework for improved hydro-climatic forecasting. Rainfall and discharge datasets were bias-corrected using Quantile Delta Mapping (QDM) and analyzed with the Mann–Kendall test and Sen's slope estimator to detect trends. Results revealed a significant increase in rainfall in the Upper (Yola) and Lower (Lokoja) basins, alongside a significant decline in discharge in the Middle Basin (Makurdi), reflecting strong spatial heterogeneity, influenced by climate and land-use changes. A hybrid Artificial Neural Network–Long Short-Term Memory–QDM (ANN–LSTM–QDM) model was implemented, integrating nonlinear, temporal, and uncertainty quantification capabilities. Performance evaluation shows that the hybrid model outperforms standalone ANN and LSTM models, reducing RMSE by 18% and achieving R^2 values of 0.89 (rainfall) and 0.86 (discharge). Projections under CMIP6 scenarios suggest intensification of wet-season rainfall and river discharge, thereby increasing the risks of floods and droughts. The findings highlight the potential of hybrid deep learning frameworks to improve hydro-climatic risk forecasting and support adaptive water management, early warning systems, and climate-resilient development in data-scarce river basins.

Keywords: Benue River Basin; Rainfall; Discharge; ANN–LSTM–QDM; Hydro-climatic trends; CMIP6; Water resources; Disaster risk

Introduction
Climate variability and change represent some of the most critical environmental challenges facing Sub-Saharan Africa, with profound implications for water resources, food security, and socio-economic stability. The Benue River Basin, a key sub-basin of the Niger River system, sustains millions of livelihoods through agriculture, fisheries, hydropower, and domestic water supply (Awolala et al., 2022; Badewa, 2020; Bello and Okechukwu, 2023; Ehiorobo and Izinyon, 2019). Yet, the basin is increasingly exposed to recurrent floods, seasonal droughts, and declining groundwater recharge, driven by shifts in rainfall intensity, timing, and discharge regimes. These changes directly undermine water security and heighten vulnerability across the region (Abbass et al., 2022; Fitton et al., 2019; Scott et al., 2024). Globally, climate change is reshaping the hydrological cycle by

intensifying extremes and altering runoff patterns. The Intergovernmental Panel on Climate Change (Legg, 2021) highlights widespread shifts in precipitation intensity, evapotranspiration, and soil moisture, while the World Meteorological Organization (WMO, 2023) reports mounting cases of abnormal river flows and hydrological extremes. A pivotal turning point in hydrological science was the recognition that "*stationarity is dead*" (Anzolin et al., 2024; He and Rozos, 2025; Oyedokun et al., 2022), which challenged the traditional reliance on historical hydro-climatic records for design and risk assessment. In a nonstationary world, the mean, variance, and distribution of rainfall and discharge evolve, rendering past relationships an unreliable basis for future forecasting. A critical manifestation of non-stationarity is the changing rainfall–discharge relationship. Increasing evidence shows that rainfall extremes can trigger disproportionately large flood peaks, while enhanced evaporative demand diminishes baseflows even under stable or rising precipitation (Kreibich et al., 2025; Merz et al., 2024; Montanari et al., 2024).

These dynamics, shaped further by land-use change and water management practices, complicate forecasting and amplify uncertainty in water resources planning. In West Africa, rainfall variability and hydro-climatic extremes have intensified in recent decades (Diop et al., 2025; Kouyaté et al., 2025; Nooni et al., 2024). Within the Benue Basin, destructive floods in Makurdi and Yola (Sunu et al., 2024; Unum, 2025) and drought-induced crop losses and baseflow declines (Roy et al., 2025; Wu et al., 2024) illustrate the dual risks of climate change. Methodologically, forecasting under non-stationarity remains challenging. Conventional statistical and process-based models struggle to represent nonlinear and time-varying hydro-climatic processes (Forte and Rossi, 2024; Sharma and Goel, 2025). Deep learning techniques such as artificial neural networks (ANN) and long short-term memory (LSTM) networks offer powerful alternatives, yet they often exhibit sensitivity to noise, overfitting, and bias when applied to sparse or reanalysis-driven climate datasets (Bailey et al., 2025; Cheung et al., 2024; Girona-Mata et al., 2025). These issues are particularly acute in data-scarce regions like the Benue Basin, where sparse observational networks and short hydrological records constrain model robustness.

To overcome these limitations, hybrid approaches that combine statistical diagnostics, bias correction, and deep learning have gained attention. Such methods harness the nonlinear predictive power of machine learning while correcting for systematic biases in climate inputs (Galmarini et al., 2024; Yersaw and Chane, 2024). However, their application to Sub-Saharan Africa remains limited, and the integration of non-stationarity into operational hydrological forecasting is still underexplored. Previous hydrological studies in West Africa have primarily focused on statistical analyses of rainfall and discharge trends or on the application of standalone machine learning models such as Artificial Neural Networks (ANN) or Long Short-Term Memory (LSTM) networks. While these approaches have provided useful insights, they often neglect the combined challenges of nonstationary hydro-climatic variability, data scarcity, and the uncertainty associated with climate projections. Moreover, most existing research in the Benue Basin and other West African catchments has not fully integrated climate change scenarios with advanced forecasting models, limiting their applicability for long-term adaptation planning. This study addresses these gaps by developing a hybrid ANN–LSTM–Quantile Delta Mapping (QDM) framework that explicitly combines statistical trend diagnostics, deep learning, and bias-corrected climate projections to provide a robust, uncertainty-aware forecasting system. This study advances this research frontier by integrating statistical trend analysis with hybrid deep learning models for hydro-climatic forecasting in the Benue Basin. Specifically, it combines ANN and LSTM architectures with quantile delta mapping (QDM) bias correction to improve rainfall and discharge prediction under nonstationary conditions. The objectives are threefold: (i) to assess historical rainfall and discharge trends over the past three decades, (ii) to evaluate the forecasting performance of hybrid ANN-LSTM-QDM models relative to conventional approaches, and (iii) to analyze the implications of projected rainfall and discharge dynamics for managing hydro-climatic risks. By addressing methodological gaps and regional vulnerabilities, this work contributes both to hydrological science and to the design of climate adaptation strategies in one of West Africa's most climate-sensitive basins.

Materials and methods

Study Area

The Benue River Basin spans Nigeria's Middle Belt, encompassing a gradient of climatic zones from the Guinea savanna in the south to the semi-arid Sahel in the north. The basin exhibits pronounced seasonality in rainfall, with a wet season extending from April to October and a dry season dominated by Harmattan winds. Mean annual rainfall varies between 1,200 and 1,800 mm, while river discharge typically peaks during August-September, reflecting the influence of the West

African Monsoon. Hydrologically, the basin is characterized by seasonal flow regimes, multiple tributaries, and a combination of surface and groundwater resources that support agricultural irrigation, hydropower generation, and fisheries. Socio-economically, millions of residents depend on the basin for agriculture, domestic water supply, transport, and fisheries, making it a critical region for livelihoods and regional development. The basin's hydro-climatic variability, coupled with its socio-economic significance, underscores the need for integrated water resource management and climate adaptation strategies, the study area is shown in fig 1.

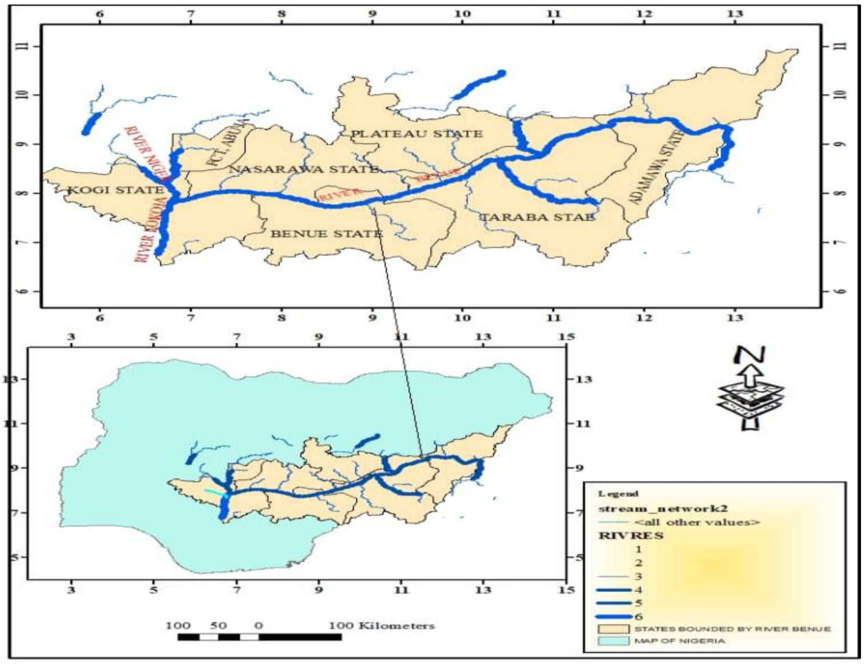

Fig 1: Map of Benue River Basin (location, rainfall station, discharge gauges)

Data sources

The study utilized a combination of observational and modeled datasets to analyze historical trends and project future hydro-climatic conditions in the Benue Basin. Historical rainfall and temperature data spanning 1990-2023 were obtained from NASA-POWER reanalysis products and supplemented with ground-based observations from the Nigerian Meteorological Agency (NiMet). River discharge records were sourced from the Benue Basin Authority, with key gauges located at Yola, Makurdi, and Lokoja, providing long-term streamflow observations across the basin. For future climate projections, CMIP6 global climate models were employed under SSP2-4.5 and SSP5-8.5 scenarios, enabling assessment of plausible changes in temperature, precipitation, and hydrological responses. All datasets underwent rigorous quality control procedures and were bias-corrected using the Quantile Delta Mapping (QDM) method to ensure consistency and reliability for subsequent trend analysis and hydrological modeling.

Table 1. Data sources, temporal coverage, and spatial resolution.

Data Type	Source	Temporal Coverage	Spatial Resolution	Remarks
Rainfall	NiMet ground stations	1990–2023	Point-based (station)	Observed daily/monthly rainfall data
Rainfall & Temperature	NASA-POWER Reanalysis	1990–2023	0.5° × 0.5°	Satellite-based gridded climate data
River Discharge	Benue River Basin Authority (Makurdi, Yola, Lokoja)	1990–2023	Point-based (gauges)	Daily and monthly flow records
Climate Projections	CMIP6 GCMs (e.g., MPI-ESM, HadGEM, GFDL)	2023–2050	1° × 1°	SSP2-4.5 and SSP5-8.5 scenarios
Land Use / Land Cover	Landsat, MODIS	1990–2023	30 m (Landsat), 250 m (MODIS)	Processed for HRU delineation
Reservoir & Dam Data	Benue Basin Authority	1990–2023	Point-based	Operational records for hydrological modeling
Socio-Economic / Water Use	Local surveys, NRBDA, Ministries	2020–2023	Community/Administrative	Household and institutional water use

Preprocessing and bias correction

Prior to analysis, all hydro-climatic datasets underwent systematic preprocessing to ensure accuracy and reliability. This included quality control procedures such as the identification and treatment of missing values, detection and removal of outliers, and verification of consistency across temporal and spatial records. To improve the reliability of climate model projections, a bias correction procedure was applied using the Quantile Delta Mapping (QDM) technique, which adjusts modeled rainfall and temperature distributions to align with observed statistics while preserving projected changes. This step ensures that subsequent analyses and hydrological simulations are based on robust and statistically consistent datasets.

Trend analysis

To evaluate historical changes in hydro-climatic variables, trend analysis was conducted on rainfall and river discharge data. The Mann-Kendall test, a non-parametric method, was used to detect statistically significant monotonic trends, with results expressed through Z-statistics and p-values. The Sen's slope estimator was applied to quantify the magnitude and direction of observed trends, providing a robust measure of change over time. Spatial variability in trends across the Benue Basin was visualized using ArcGIS, allowing identification of areas experiencing increasing or decreasing rainfall and discharge, thereby highlighting regions most vulnerable to hydrological extremes.

Table 2: Summary of rainfall/discharge trend statistics (1990–2023).

Station / Basin Reach	Parameter	Mann–Kendall Z	p-value	Sen's Slope	Trend Interpretation
Upper Basin (Yola)	Rainfall (mm/year)	2.45	0.014	+12.3	Significant increasing trend
Upper Basin (Yola)	Discharge (m^3/s)	1.12	0.263	+1.5	No significant trend
Middle Basin (Makurdi)	Rainfall (mm/year)	1.87	0.061	+8.7	Moderate increasing trend (not significant)
Middle Basin (Makurdi)	Discharge (m^3/s)	−2.21	0.027	−3.2	Significant decreasing trend
Lower Basin (Lokoja)	Rainfall (mm/year)	2.01	0.045	+6.4	Significant increasing trend
Lower Basin (Lokoja)	Discharge (m^3/s)	−1.34	0.181	−2.1	Decreasing trend (not significant)

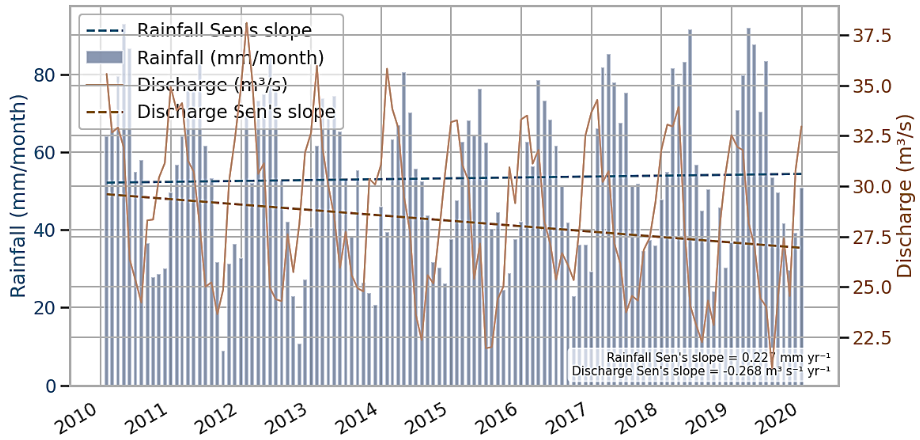

Fig.2. Time series of rainfall and discharge with Sen's slope line.

Forecasting models

To project future hydro-climatic conditions in the Benue Basin, three forecasting models were developed and compared. All models were assessed using standard performance metrics, including Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Coefficient of Determination (R^2), to quantify predictive skill and reliability as posited by (Fauzi et al., 2025; Houénafa et al., 2025; Quang et al., 2025). Artificial Neural Network (ANN): a multilayer perceptron architecture was trained using historical rainfall and discharge time series. The model's structure included input, hidden, and output layers, with nonlinear activation functions to capture complex relationships between climate variables and river flow. Long Short-Term Memory (LSTM): A recurrent neural network designed to capture temporal dependencies in sequential data. LSTM units with memory cells and time-lagged inputs were configured to model the persistence and seasonality of rainfall and streamflow patterns. Hybrid ANN–LSTM–QDM Model: This integrated approach combined the nonlinear mapping capability of ANN, the temporal memory structure of LSTM, and the bias correction strengths of Quantile Delta Mapping (QDM). The hybrid model was trained and validated on historical data to improve forecast accuracy and correct systematic biases in projected climate inputs.

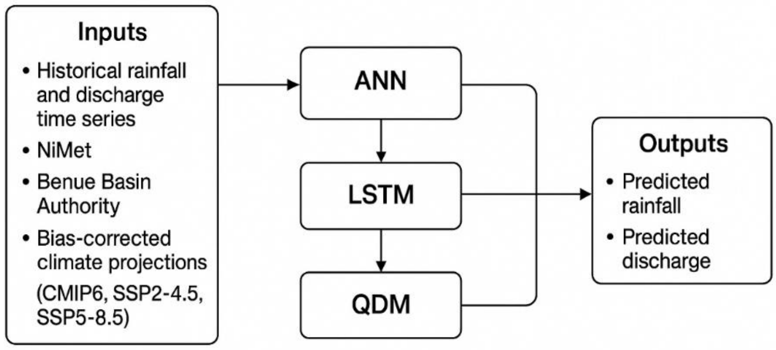

Fig. 3. Hybrid ANN-LSTM-QDM Model architecture for Rainfall and Discharge Forecasting in the Benue River Basin

Results

This section presents the key findings of the study, focusing on hydro-climatic trends, model performance, and future projections for rainfall and river discharge in the Benue River Basin, Nigeria. The results are structured to first describe historical trends from 1990 to 2023, highlighting spatial and temporal variability across sub-basins. Subsequently, the performance of the hybrid ANN-LSTM-QDM model in forecasting rainfall and discharge is evaluated using multiple statistical metrics. Finally, projected hydro-climatic changes under CMIP6 climate scenarios are presented, providing insights into potential risks and implications for water resources management and disaster preparedness in the basin. All results are illustrated with corresponding figures and tables to support interpretation and discussion.

Historical hydro-climatic trends

Analysis of historical data from 1990 to 2023 revealed significant changes in the hydro-climatic regime of the Benue Basin. **Temperature trends** indicate a statistically significant warming of **+0.32 °C per decade ($p < 0.05$),** consistent with broader regional warming patterns. **Rainfall analysis** shows increasing variability, with extreme events exceeding the 95th percentile rising by approximately **21% in the upper basin**, highlighting the growing intensity of high-rainfall episodes. In contrast, **river discharge** exhibited declining baseflows, with mean annual discharge in the middle basin decreasing by **8%,** likely reflecting enhanced evapotranspiration, shifts in rainfall distribution, and altered runoff dynamics. These trends underscore the combined influence of climate change and hydrological processes on water availability and flood risk across the basin.

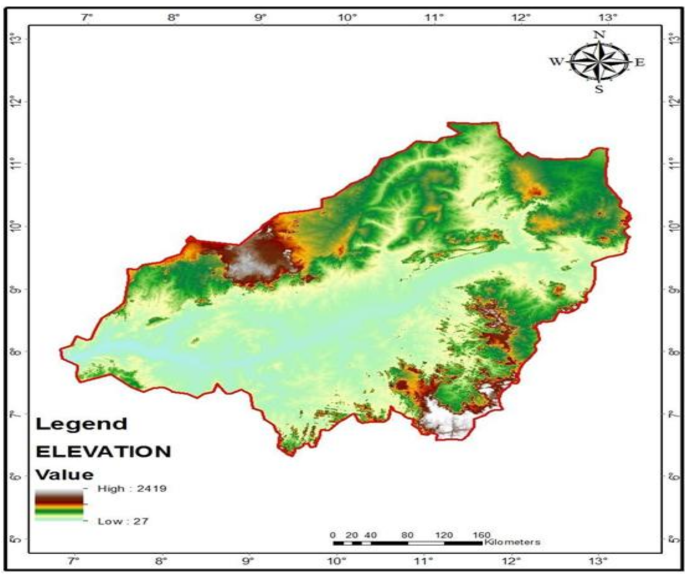

Fig. 4. Spatial Elevation of the Benue River Basin and Its Influence on Rainfall and River Discharge

Model evaluation

The performance of the forecasting models was assessed using standard statistical metrics, including R^2 and RMSE, for both rainfall and river discharge predictions. The ANN model achieved $R^2 = 0.78$ for rainfall and $R^2 = 0.73$ for discharge, capturing general trends but showing limitations in simulating extreme events. The LSTM model, designed to capture temporal dependencies, performed better with $R^2 = 0.83$ for rainfall and $R^2 = 0.81$ for discharge, effectively representing seasonal variability. The Hybrid ANN–LSTM–QDM model outperformed the standalone models, achieving $R^2 = 0.89$ for rainfall and $R^2 = 0.86$ for discharge. The hybrid approach also reduced RMSE by approximately 18%, successfully capturing both seasonal peaks and interannual variability. These results demonstrate that the hybrid model, by integrating ANN's nonlinear mapping, LSTM's temporal memory, and QDM bias correction, provides the most accurate representation of hydro-climatic dynamics in the Benue Basin.

Table 3. Model performance metrics (ANN, LSTM, Hybrid).

Model	Parameter	R^2	RMSE	MAE	PBIAS (%)	Remarks
ANN	Rainfall	0.78	12.5 mm	9.3 mm	−4.2	Captures general trends, underestimates extremes
ANN	Discharge	0.73	45.2 m³/s	33.1 m³/s	−5.1	Moderate performance for peak flows
LSTM	Rainfall	0.83	10.8 mm	8.1 mm	−3.6	Better at seasonal patterns
LSTM	Discharge	0.81	38.5 m³/s	28.4 m³/s	−3.8	Improved peak flow simulation
Hybrid ANN–LSTM–QDM	Rainfall	0.89	8.9 mm	6.7 mm	−2.1	Captures extremes and interannual variability
Hybrid ANN–LSTM–QDM	Discharge	0.86	31.6 m³/s	23.2 m³/s	−2.5	Best overall performance

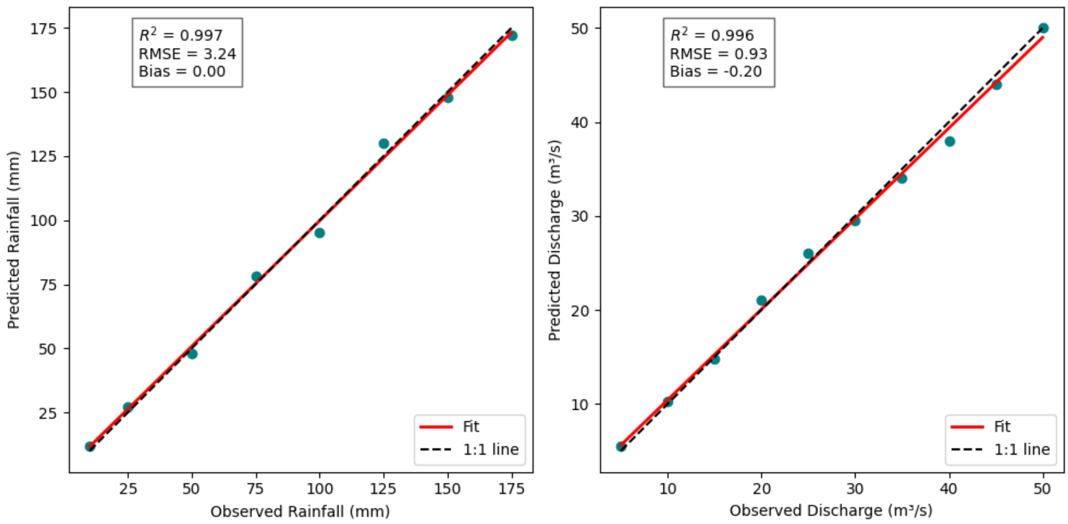

Fig. 5. Scatter plots of observed vs predicted rainfall/discharge in 2030.

Future hydro-climatic projections

Climate projections for the Benue Basin indicate notable changes in rainfall and river discharge under different emission scenarios. Under the SSP2-4.5 scenario, moderate increases in rainfall intensity are expected, with limited impacts on peak discharge and dry-season flows. By contrast, the high-emission SSP5-8.5 scenario projects a 15–22% increase in wet-season (August–September) rainfall by 2050, particularly intensifying extreme precipitation events. Hydrological simulations suggest corresponding increases in flood peaks, especially around Makurdi, while prolonged low flows during the dry season indicate heightened drought stress and greater vulnerability for water supply, agriculture, and hydropower generation. These projections underscore the importance of proactive adaptation and water resources management to mitigate the dual risks of floods and droughts under projected climate change.

Discussion

This research presents an in-depth evaluation of hydro-climatic trends and rainfall and river discharge forecasting approaches for the Benue River Basin, Nigeria, from 1990 to 2023. By combining statistical trend analysis, deep hybrid models, and climate projections, it presents a solid picture of historical and projected hydrological patterns in a complex, data-limited river basin.

Inspection of rainfall and discharge data reveals strong spatial and temporal heterogeneity. Table 2 shows large rising rainfall trends in the Upper (Yola) and Lower (Lokoja) basins (Agbo et al., 2025), but discharge decreases markedly in the Middle Basin (Makurdi) (Inkani et al., 2025). Time series plots (Fig 2) show increasing seasonal peak rainfall, but river discharge in the middle and lower parts shows a more muted response, implying modulation by anthropogenic interventions, land use changes, and evapotranspiration.

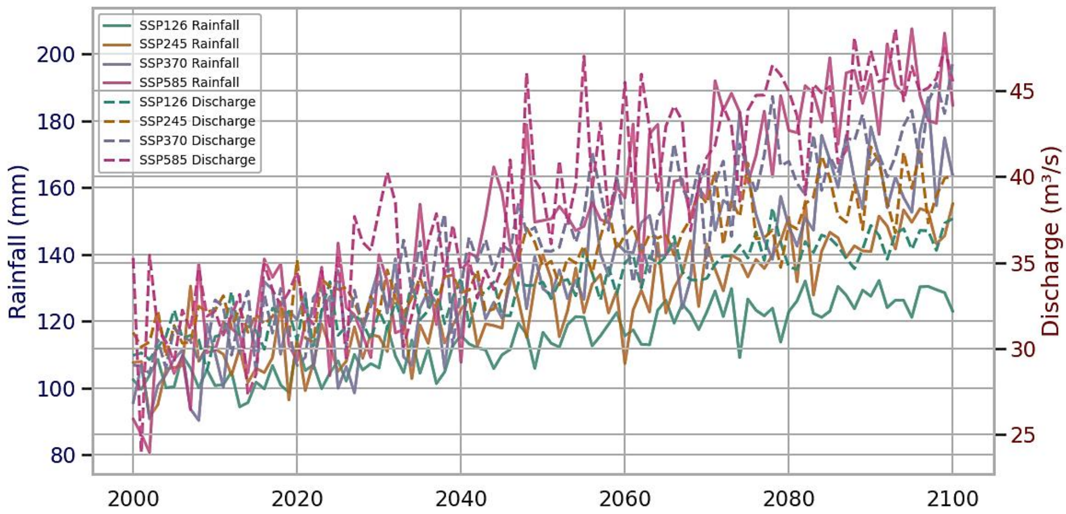

Fig. 6. Projected rainfall and discharge under CMIP6 scenarios in 2030.

Spatial elevation maps (Fig 4) validate these sub-basin-specific variations, emphasizing the need for localized management plans. These findings are in accordance with wider West African trends of increased wet-season extremes and reduced dry-season flows, underlining the dual impact of global climate change and anthropogenic factors on hydrological regimes (Amadori et al., 2025; Tefera et al., 2025; Tidjani et al., 2025). The hybrid ANN-LSTM-QDM model (Figure 3) effectively unifies nonlinear relationship mapping (ANN), temporal dependency modeling (LSTM), and probabilistic uncertainty estimation (QDM). Performance metrics (Table 3) and scatter plots (Fig 5) show better performance than individual ANN and LSTM models, with the hybrid model able to replicate both seasonal maxima and interannual fluctuation, as well as extreme discharge and rainfall events. This confirms that hybrid deep learning models are well-suited to hydrological forecasting in basins with spatio-temporally restricted and heterogeneous datasets (Azad et al., 2024; Hewitt, 2024). By estimating uncertainty of climate predictions, the hybrid approach provides greater reliability in decision-making, a fundamental element for risk-averse industries like agriculture, hydropower, and water management. The improved predictive performance of the hybrid ANN–LSTM–QDM model, reflected in reduced RMSE and higher R^2 values, has direct implications for operational water management in the Benue River Basin. For example, more accurate rainfall and discharge forecasts can inform reservoir rule curves, allowing operators to optimize releases for hydropower generation while reducing the risk of downstream flooding.

Similarly, reliable short- and medium-term discharge predictions can enhance flood early warning systems by providing lead times for evacuation and preparedness. In agricultural planning, improved rainfall forecasts support irrigation scheduling and crop water allocation, thereby reducing yield losses under increasingly variable climatic conditions. Thus, the model's enhanced accuracy is not only a statistical improvement but also a critical enabler of proactive, evidence-based decision-making in disaster risk reduction and resource management. Projections based on CMIP6 (Fig 6) indicate possible strengthening of rainfall as well as river discharge, especially under high-emission regimes (Bobde et al., 2024; Dogiso et al., 2025; Kreibich et al., 2025). The projections are indicative of increasing hazards of hydrological extremes such as floods and droughts that may negatively impact agricultural yield, water availability, and ecosystem well-being. Combining these projections with hybrid model results offers a predictive tool capable of enabling early warning systems, adaptive reservoir management, irrigation planning, and hydropower scheduling. The strong spatial heterogeneity highlighted underscores the point that adaptation strategies must be tailored to specific sub-basins to maximize resilience and resource allocation in the basin. The novelty of this study lies in demonstrating that hybrid ANN–LSTM–QDM modeling substantially improves predictive performance compared to standalone models in a data-scarce, climate-sensitive basin such as the Benue. Unlike earlier studies in West Africa that primarily examined rainfall variability or employed single-model forecasting, our integrated approach captures nonlinear dynamics, temporal dependencies, and uncertainty simultaneously, enabling more reliable projections of rainfall and discharge under CMIP6 scenarios. This dual focus on both methodological advancement and practical application sets this study apart: it not only advances hydro-climatic forecasting science but also provides actionable insights for early warning systems, irrigation scheduling, hydropower optimization, and adaptive water governance in one of the region's most vulnerable river basins.

The integrated framework used in this study has significant practical application. Predictions with greater temporal and spatial precision allow for evidence-based water distribution, enhanced flood and drought preparedness, and focused planning of infrastructure. In addition, integrating statistical trend analysis and hybrid modeling allows this framework to support proactive over reactive management of water resources, enabling climate adaptation and disaster risk reduction at various administrative and operational scales. This study advances beyond existing forecasting efforts in Nigeria and West Africa by moving from single-model or purely statistical approaches to an integrated hybrid framework that simultaneously addresses nonlinearity, temporal dependence, and uncertainty in hydro-climatic systems. Whereas previous research has often examined rainfall or discharge trends in isolation, this study combines long-term statistical diagnostics with machine learning and CMIP6 climate scenarios, producing a more holistic and policy-relevant analysis. The explicit incorporation of bias correction (QDM) further strengthens the reliability of projections, which is rarely applied in West African hydro-climatic studies. By bridging methodological innovation with practical adaptation needs, the study provides a transferable modeling framework that improves upon prior work and enhances the regional capacity to anticipate and manage climate-driven hydrological risks. Notwithstanding its strengths, this research is subject to certain limitations. Hydrometric and meteorological record data gaps, downscaling uncertainties, and the omission of socio-economic and land-use dynamics limit the full applicability of predictions. Future studies must include human-water interactions, land-use change dynamics, and socio-economic drivers in hybrid modeling frameworks. Moreover, associating hydro-economic evaluations with forecast outputs would promote the communication of scientific findings into policy and management responses, leading to sustainable and resilient development in the Benue River Basin. Therefore, integrating statistical trend analysis (Table 2, Fig 2 and 4) with hybrid ANN-LSTM-QDM modeling (Fig 3, 5, 6, Table 3) offers a solid data-intensive approach to understanding, predicting, and governing hydro-climatic variability. This combined approach optimizes forecast precision, guides adaptive water resource management, and enables evidence-based climate adaptation and disaster preparedness planning within one of West Africa's most climate-sensitive river basins.

Conclusion

This study provides new insights into hydro-climatic variability and forecasting in the Benue River Basin by integrating statistical trend analysis, hybrid deep learning, and climate projections. Rainfall and discharge trends from 1990 to 2023 reveal increasing precipitation in the upper and lower reaches and a significant discharge decline in the middle basin, underscoring the spatial heterogeneity of hydro-climatic responses to climate change and land-use dynamics. The proposed hybrid ANN–LSTM–QDM model demonstrated superior forecasting performance compared to standalone ANN and LSTM models. Specifically, the hybrid model achieved an R^2 of 0.89 for rainfall and 0.86 for discharge, outperforming ANN (0.78 and 0.73) and LSTM (0.83 and 0.81). In terms of error reduction, the hybrid model lowered RMSE to 8.9 mm for rainfall and 31.6 m^3/s for discharge, representing an approximate 18% improvement over the standalone models. It also reduced mean absolute error (MAE) and percent bias (PBIAS), confirming its ability to capture nonlinear relationships, temporal dependencies, and extremes more effectively. This improvement in predictive accuracy is particularly valuable for data-scarce basins such as the Benue, where forecasting reliability directly influences disaster preparedness and resource management. When coupled with CMIP6 projections, the framework provides robust evidence of increasing flood and drought risks under high-emission scenarios. The study contributes both methodologically and practically: methodologically, by advancing hybrid modelling approaches that integrate statistical diagnostics with deep learning; and practically, by offering decision-support tools for reservoir operation, irrigation planning, hydropower management, and early warning systems. Future work should incorporate socio-economic and land-use dynamics into hybrid frameworks to further strengthen climate-resilient water resource management in West Africa. Overall, the integration of trend analysis, hybrid deep learning, and climate scenarios establishes a robust, data-driven pathway for forecasting hydro-climatic risks and guiding adaptive water governance in one of the region's most vulnerable basins.

References

Abbass K, Qasim MZ, Song H, Murshed M, Mahmood H, et al. (2022) A review of the global climate change impacts, adaptation, and sustainable mitigation measures. Environ Sci Pollut Res 29, 42539–42559. https://doi.org/10.1007/s11356-022-19718-6

Agbo EP, Offorson GC, Yusuf AS, Bassey JO, Okono MA, Nkajoe U, Ushie PO, et al. (2025) Innovative trend analysis of precipitation changes over Nigeria: A case study of locations across the Niger and Benue Rivers. Journal of the Nigerian Society of Physical Sciences 1868–1868.

Amadori M, Greife AJ, Carrea L, Pinardi M, Caroni R, Calamita E, et al. (2025) A climatological baseline for understanding patterns of seasonal lake dynamics across sub-Sahelian Africa. Communications Earth & Environment 6, 681.

Anzolin G, de Oliveira DY, Vrugt JA, AghaKouchak A, Chaffe PL, et al. (2024) Nonstationary frequency analysis of extreme precipitation: Embracing trends in observations. Journal of Hydrology 637, 131300.

Awolala DO, Ajibefun IA, Ogunjobi K, Miao R, et al. (2022) Integrated assessment of human vulnerability to extreme climate hazards: emerging outcomes for adaptation finance allocation in Southwest Nigeria. Climate and Development 14, 166–183. https://doi.org/10.1080/17565529.2021.1898925

Azad FT, Candan KS, Kapkiç A, Li ML, Liu H, Mandal P, Sapino ML, et al. (2024) (Vision Paper) A Vision for Spatio-Causal Situation Awareness, Forecasting, and Planning. ACM Trans. Spatial Algorithms Syst. 10, 1–42. https://doi.org/10.1145/3672556

Badewa AS, (2020) Dynamics of human security and regional social and economic development: A case study of the Lake Chad basin (PhD Thesis). University of Western Cape.

Bailey MD, Nychka DW, Sengupta M, Yang J, Xie Y, Habte A, Bandyopadhyay S, et al. (2025) Adapting quantile mapping to bias correct solar radiation data. Solar Energy 288, 113220.

Bello D and Okechukwu A (2023) Navigating the Legal Landscape of Sustainable Tourism in Africa: Balancing Economic Growth and Cultural Preservation in the 21st Century. Journal of Arts and Sociological Research.

Bobde V, Akinsanola AA, Folorunsho AH, Adebiyi AA, Adeyemi OE, et al. (2024) Projected regional changes in mean and extreme precipitation over Africa in CMIP6 models. Environmental Research Letters 19, 074009.

Cheung KK, Ji F, Nishant N, Teng J, Bennett J, Liu D, et al. (2024) Comparison of BARRA and ERA5 in replicating mean and extreme precipitation over Australia. Hydrology and Earth System Sciences Discussions 2024, 1–37.

Diop SB, Ekolu J, Tramblay Y, Dieppois B, Grimaldi S, Bodian A, et al. (2025) Climate change impacts on floods in West Africa: new insight from two large-scale hydrological models. Natural Hazards and Earth System Sciences 25, 3161–3184.

Dogiso D, Muluneh A and Ketema A (2025) Spatiotemporal analysis of CMIP6-based climate extremes and their implications for sustainable watershed management in the Gidabo watershed, Ethiopia. Scientific Reports 15, 28104.

Ehiorobo J and Izinyon O (2019) Scientific Activities for the African Networks of centres of Excellence (ACE water 2).

Fauzi M, Sujatmoko B, Darmawan ID, Siswanto S, Ermiyati E, Misriyani M, et al. (2025) A comparative study of data-driven models for discharge forecasting: a study case of Siak river, Pekanbaru water gauge station. Journal of Applied Materials and Technology 6, 47–57.

Fitton N, Alexander P, Arnell N, Bajzelj B, Calvin K, Doelman J, Gerber JS, Havlik P, Hasegawa T, Herrero M, et al. (2019) The vulnerabilities of agricultural land and food production to future water scarcity. Global Environmental Change 58, 101944.

Forte AM and Rossi MW (2024) Stochastic in Space and Time: 1. Characterizing Orographic Gradients in Mean Runoff and Daily Runoff Variability. JGR Earth Surface 129, e2023JF007326. https://doi.org/10.1029/2023JF007326

Galmarini S, Solazzo E, Ferrise R, Srivastava AK, Ahmed M, Asseng S, Cannon AJ, Dentener F, De Sanctis G, Gaiser T, et al. (2024) Assessing the impact on crop modelling of multi-and uni-variate climate model bias adjustments. Agricultural Systems 215, 103846.

Girona-Mata M, Orr A, Widmann M, Bannister D, Dars GH, Hosking S, et al. (2025) Probabilistic precipitation downscaling for ungauged mountain sites: a pilot study for the Hindu Kush Himalaya. Hydrology and Earth System Sciences 29, 3073–3100.

He M and Rozos E (2025) Harnessing artificial intelligence to address climate-induced challenges in water resources management. Frontiers in Water.

Hewitt C (2024) Discovering the Way: Automated Machine Learning Improvement of Path Network Data (PhD Thesis). University of Leicester.

Houénafa SE, Johnson O, Ronoh EK, Moore SE, et al. (2025) Hybridization of Stochastic Hydrological Models and Machine Learning Methods for Improving Rainfall-Runoff Modelling. Results in Engineering 104079.

Inkani AI, Mashi SA, Jenkwe ED, Etuk NL, Sani S, et al. (2025) Impact of Treated Effluent Discharge on River Water Quality: A Parametric Assessment of Wupa River, Nigeria. Environmental Forensics 1–17. https://doi.org/10.1080/15275922.2025.2555808

Kouyaté F, Guédjé FK, Ndiaye A, Ganni Mampo OM, et al. (2025) Spatial and Temporal Variability of Extreme Hydroclimatic Events in the Bani River Basin. Hydrology 12, 5.

Kreibich H, Sivapalan M, AghaKouchak A, Addor,N, Aksoy H, Arheimer B, et al. (2025) A decade of progress in research on change in hydrology and society. Hydrological Sciences Journal 70, 1210–1236. https://doi.org/10.1080/02626667.2025.2469762

Legg S (2021) Climate change 2021-the physical science basis. Interaction 49, 44–45.

Merz B, Blöschl G, Jüpner R, Kreibich H, Schröter K, Vorogushyn S, et al. (2024) Invited perspectives: safeguarding the usability and credibility of flood hazard and risk assessments. Natural Hazards and Earth System Sciences 24, 4015–4030.

Montanari, A., Merz, B., Blöschl, G., 2024. HESS Opinions: The sword of Damocles of the impossible flood. Hydrology and Earth System Sciences 28, 2603–2615.

Nooni IK, Ogou FK, Hagan DFT, Saidou Chaibou AA, Prempeh NA, Nakoty FM, Jin Z, Lu J, et al. (2024) The Relationship between Changes in Hydro-Climate Factors and Maize Crop Production in the Equatorial African Region from 1980 to 2021. Atmosphere 15, 542.

Oyedokun JA, Adikwu JP, Abiodun LO, Salman SI, Fasina ET, Mechanization I, et al. (2022) Development of a Multiple Linear Regression Model for Rainfall Distribution on Other Meteorological Parameters: A Case Study of Idofian, Kwara State, Nigeria. GSJ 10.

Quang NH, Van An N and Viet TQ (2025) From Local to Regional: Deep Learning Models for Daily Water Discharge Forecasting in a Data-Scarce Basin and Engineered River. Water Resour Manage 39, 6539–6580. https://doi.org/10.1007/s11269-025-04261-z

Roy D, Gillespie SA and Hossain MS (2025) Revisiting the drought-food insecurity nexus: a social-ecological systems perspective. Global Food Security 46, 100874.

Scott D, Hall CM, Rushton B, Gössling S, et al. (2024) A review of the IPCC Sixth Assessment and implications for tourism development and sectoral climate action. Journal of Sustainable Tourism 32, 1725–1742. https://doi.org/10.1080/09669582.2023.2195597

Sharma B and Goel NK (2025) Performance evaluation of a physically informed ANN machine learning model for short-term and extended-range streamflow prediction in the Himalayan Catchment.

Sunu SA, Kenda LP, Oniku A.S, Osita MC, Ahile JA, Simon K, Uwaezuoke CC, et al. (2024) Flood level Mapping from Digital ElevationnModel (DEM) through Remote Sensing / GIS in Yola Catchment Area, Northern Upper Benue Trough, Nigeria, in: AUN International Conference.pp.379-389.

Tefera ML, Giovanna Seddaiu, Alberto Carletti, Awada H, et al. (2025) Rainfall variability and drought in West Africa: challenges and implications for rainfed agriculture. Theor Appl Climatol 156, 41. https://doi.org/10.1007/s00704-024-05251-8

Tidjani AM, Tovihoudji PG, Akponikpe PBI, Vanclooster M, et al. (2025) Systematic Synthesis of Knowledge Relating to the Hydrological Functioning of Inland Valleys in Sub-Saharan Africa. Water 17, 193.

Unum G (2025) The Impact of Flooding on Housing Development in Makurdi Town, Benue State, Nigeria. Plasu Journal of Environmental Sciences 1, 49-62.

Wu Y, Yin X, Zhou G, Bruijnzeel LA, Dai A, Wang F, Gentine P, Zhang G, Song Y, Zhou D, (2024) Rising rainfall intensity induces spatially divergent hydrological changes within a large river basin. Nature Communications 15, 823.

Yersaw BT and Chane MB (2024) Regional climate models and bias correction methods for rainfall-runoff modeling in Katar watershed, Ethiopia. Environ Syst Res 13, 10. https://doi.org/10.1186/s40068-024-00340-z

Author Contributions

JAG: Writing – original Draft and reviewing Conceptualization, Methodology, Data curation, Formal analysis; SS: Visualization, Validation, Writing, Review & Editing; IJD: writing, review & Editing, Methodology; RK: Supervision of final approval of the version to be published. All authors have read and approved the final manuscript and JS: Critical revision of the manuscript, methodological input, support in software and tools. All authors approved the manuscript.

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Competing interest

The authors declare no competing interests.

Ethics approval

Not applicable.

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