

Rainfall extremes and runoff dynamics in Lokoja using HEC-HMS: a hydro-climate modeling approach

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ABSTRACT

The hydrological modeling methodology integrates climate and hydrological frameworks to scrutinize the ramifications of climatic variability on aquatic systems, underscoring the necessity of comprehending rainfall-runoff dynamics in Lokoja for the formulation of efficacious flood management and climate adaptation strategies. This study analyzed rainfall-runoff responses using a data-driven hydrological model to identify seasonal rainfall patterns and evaluate flood risk through simulation outputs. Daily rainfall and runoff data from 2010 to 2023, obtained from the Nigerian Meteorological Agency (NiMet), were analyzed using a Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS)-inspired framework. Model calibration and validation were conducted using the Nash-Sutcliffe efficiency coefficient, while impulse response functions were employed to compare observed and simulated data. Results indicated the rainfall distribution with a peak (~320 mm) in August and dry conditions from November to April. Significant anomalies occurred in 2012, 2017, and 2022—years marked by heightened flood events—while 2015, 2016, and 2021 displayed drought-like tendencies. Runoff often exceeded 100 m³/s and revealed a near-perfect statistical correlation ($r = 1.0$) between annual rainfall and modeled runoff with a regression slope of 0.1484 m³/s per mm of rainfall. The model effectively captured the hydrological response of Lokoja's watershed, highlighting the significant influence of rainfall anomalies on runoff patterns. These findings reinforce the importance of predictive modeling for flood risk assessment. Future studies should integrate climate forecasts and land use change assessments to enhance hydrological predictions and inform sustainable flood mitigation strategies.

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1. Introduction

Understanding the extreme impact of rainfall on hydrological runoff is vital for proficient hydrological system management, especially in flood-vulnerable regions. Extreme precipitation occurrences, distinguished by their elevated intensity and short duration, exert a considerable effect on runoff generation, leading to the swift accumulation of surface water and an augmented risk of flooding. This phenomenon holds particular relevance in flood-prone areas where intense rainfall often surpasses the capacity of both natural and engineered drainage infrastructures.

Consequently, the repercussions observed are flash floods, soil erosion, and water quality degradation (Apel et al., 2009). Considering these challenges, hydrological modeling emerges as an essential tool for predicting runoff behavior under extreme conditions, thereby providing critical insights for disaster preparedness and the management of water resources (He et al., 2024). Within this framework, one locale where the impacts of extreme precipitation are notably significant is Lokoja, a city located at the confluence of the Niger and Benue rivers in Nigeria. Owing to its



geographical setting, Lokoja demonstrates an increased susceptibility to flooding, particularly during the rainy season when intense rainfall triggers riverine and pluvial flooding (Buba et al., 2021). As a low-lying urban entity, Lokoja's vulnerability to such flooding occurrences is intensified by the limited capacity of its soil and drainage systems to manage excess water effectively.

Oyedele et al. (2022) reported that the city shows a substantially higher likelihood of flooding than other regions. Contributory elements encompass inadequate building designs, a lack of efficient flood management and evacuation protocols, an overreliance on agriculture by local communities, restricted economic diversification, and insufficient household financial resilience. Thus, hydrological models, particularly the Hydrologic Engineering Centers Hydrologic Modeling System (HEC-HMS), are vital for simulating runoff responses and elucidating the ramifications of extreme weather phenomena. Furthermore, in light of Lokoja's vulnerability to flooding, the execution of hydro-climate analysis becomes increasingly critical. Hydro-climate analysis, which amalgamates climate variability with hydrological processes, enhances the evaluation of flood risks, particularly in areas frequently impacted by extreme weather phenomena (Sahani et al., 2019). In regions affected by flooding, such as Lokoja, modeling systems like HEC-HMS are indispensable for flood forecasting, watershed management, and the facilitation of urban development planning. These instruments permit the simulation of the effects of extreme rainfall on runoff, enabling the anticipation of runoff volume, peak discharge, and time-to-peak after significant meteorological events (Singh, 2017). The HEC-HMS thus allows researchers and policymakers to formulate more effective flood control strategies and mitigate the socio-economic consequences of flooding. Moreover, as climate change continues to shape global meteorological patterns, the importance of hydro-climate studies is witnessing substantial augmentation. In regions such as Lokoja, where the challenges associated with extreme precipitation are increasingly urgent, modeling runoff dynamics is essential for fostering sustainable development and enhancing disaster risk reduction strategies (Nouhou et al., 2025). By synthesizing climate considerations with

hydrological phenomena, scholars are more enlightened in decisions about flood mitigation and resilience within susceptible communities. The application of HEC-HMS in Lokoja is a pertinent illustration of the overarching significance of hydro-climate modeling in elucidating and managing the consequences of extreme precipitation on runoff, thus facilitating more sustainable urban planning methodologies and refined disaster preparedness strategies.

On a global scale, the increased frequency and intensity of extreme precipitation events, attributable to climate change, profoundly impact hydrological systems. Empirical investigations have demonstrated that precipitation is a critical factor in flood risks, alteration of river discharge patterns, and increased soil erosion (Okacha et al., 2024). Within the African continent, these effects are in urban settings such as Lokoja, Nigeria, where the vulnerability to flooding is increasingly evident (Oyedele et al., 2022). Regional studies clarify the complex ways climate variability and human activities—like urbanization and land use changes—worsen these challenges. As a result, analytical tools such as HEC-HMS are deemed essential for predicting runoff dynamics and informing flood management frameworks (Babu and Kumar, 2024). Understanding runoff mechanisms further emphasizes the need for enhanced hydrological modeling. Soil properties, including permeability, play a crucial role in determining the volume of precipitation that infiltrates the soil compared to that which is transformed into surface runoff (Joshi, 2023; Manjunatha et al., 2024). Regions with compacted or less permeable soils generate more runoff during extreme precipitation (Rammal and Berthier, 2020). Changes in land use, including deforestation and urban expansion, significantly influence runoff patterns by reducing infiltration and increasing surface water accumulation in urbanized zones (Muhangane et al., 2024). This phenomenon is particularly salient in Nigerian urban centers, where rapid urbanization has resulted in substantial shifts in runoff dynamics (McGrane, 2016; Gilbert and Shi, 2023).

Another critical factor affecting runoff is the interplay of topography, land use, and soil properties. Steeper slopes promote accelerated runoff, while flatter landscapes retain larger volumes of water (Li et al., 2020). Lokoja's

varied terrain and proximity to water increase flood risks during extreme precipitation (Aladejana and Ebijuoworih, 2024). Hydrological models such as HEC-HMS offer valuable insights into these dynamics, facilitating more accurate flood risk assessments and enhanced disaster preparedness approaches. HEC-HMS and SWAT are prominent hydrological modeling tools for forecasting runoff. Hydrological processes and flood events in regions facing extreme climates are forecasted using these models. HEC-HMS, in particular, has exhibited efficacy in rainfall-runoff analysis owing to its ability to simulate the comprehensive hydrological cycle (Ranjan and Singh, 2020). The model's adaptability for simulating various watershed conditions, seamless GIS integration, and climate variability impact assessment on water systems are key features (Scharffenberg, and Fleming, 2006; Surendran et al., 2021).

In Nigeria, hydro-climatic studies increasingly highlight the critical analysis of climatic extremes' impacts on flood risk and runoff. Lokoja acknowledged as one of Nigeria's most susceptible urban locales to flooding, has attracted substantial academic scrutiny. Prior investigations have examined the intricate relationships among extreme precipitation events, river discharge metrics, and flooding occurrences, particularly within the confluence area of the Niger and Benue rivers (Aich, 2014; Abah and Petja, 2017; Ifatimehin et al., 2020). Nonetheless, the exacerbation of flood-related hazards attributable to climate change, which amplifies the intensity of precipitation extremes, presents a pressing challenge in Lokoja and across the broader Nigerian context (Odjugo, 2010; Aladejana, and Ebijuoworih, 2024). This investigation enhances traditional runoff modeling methodologies by integrating the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) with downscaled climatic forecasts. It validates the outcomes through comparative modeling and sensitivity assessments and correlates the results with Geographic Information System (GIS) based floodplain delineations. These methodological advancements provide a thorough and spatially explicit understanding of the interactions between precipitation and runoff processes, as well as the associated flood risks in Lokoja, applicable to both contemporary and prospective climate

scenarios. This establishes a novel framework for decision-making in adaptive flood management.

2. Material and methods

2.1. Study area

Lokoja, which serves as the administrative capital of Kogi State and is situated in central Nigeria, is strategically positioned at the confluence of the Niger and Benue Rivers, thereby bestowing upon it unique geographical and hydrological significance. Geographically located at approximately latitude 7°45'0"N to 7°53'30"N and longitude 6°43'0"E to 6°51'30"E, Lokoja occupies a pivotal junction where Nigeria's two principal rivers converge, rendering it a city of considerable strategic importance for waterborne transportation, agricultural endeavors, and fishing activities. The topographical elevation of the city varies between 50 and 120 meters above sea level, characterized by a landscape that comprises both low-lying floodplains and gentle hill formations. This topographical heterogeneity profoundly affects runoff patterns, wherein low-lying areas exhibit a pronounced susceptibility to flooding during intense precipitation while elevated regions demonstrate rapid runoff under comparable conditions (Oyedele et al., 2024). Lokoja's undulating hills influence water flow and runoff generation, especially in the rainy season. The presence of these hills facilitates the development of natural drainage systems that guide rainwater toward the floodplains, thereby heightening flood risks during extreme rainfall events. The floodplains that abut the confluence of the Niger and Benue Rivers are particularly vulnerable to waterlogging and flash flooding when upstream precipitation from surrounding areas contributes to the swelling of the rivers. Climatically, Lokoja is characterized by a tropical savanna climate, which is defined by distinct wet and dry seasons. The rainy season generally extends from April to October, with peak precipitation typically occurring between July and September. The average annual precipitation varies between 1,000 to 1,500 mm; however, episodes of extreme rainfall can substantially surpass this average, resulting in sudden and severe runoff (Ndukson et al., 2021). Such extreme rainfall events are frequently instigated by the West African

Monsoon, which transports moisture-laden winds from the Atlantic Ocean during the wet season. Furthermore, Lokoja is affected by the Intertropical Convergence Zone (ITCZ), a significant climatic phenomenon that induces variability in rainfall patterns, thereby contributing to episodes of intense precipitation (Francis et al., 2025). In the dry season, spanning from November to March, Lokoja experiences markedly reduced rainfall, with temperatures oscillating between 25°C and 40°C. The Harmattan, a dry and dusty trade wind originating from the Sahara, predominates during this period, resulting in cooler temperatures, reduced humidity, and minimal precipitation. This pronounced wet-dry

seasonal cycle leads to highly variable hydrological conditions in the region, rendering the city particularly sensitive to fluctuations in rainfall intensity and runoff dynamics. The city's vulnerability to flooding is exacerbated by its geographical location at the confluence of two significant rivers, which frequently overflow during episodes of extreme rainfall, thereby heightening flood risks (Nouhou et al., 2025). In recent years, the implications of climate change have intensified these risks by increasing the frequency of extreme rainfall events, thereby underscoring the urgent necessity for comprehensive hydro-climate analysis. The map of Lokoja, Nigeria, is shown in Fig. 1.

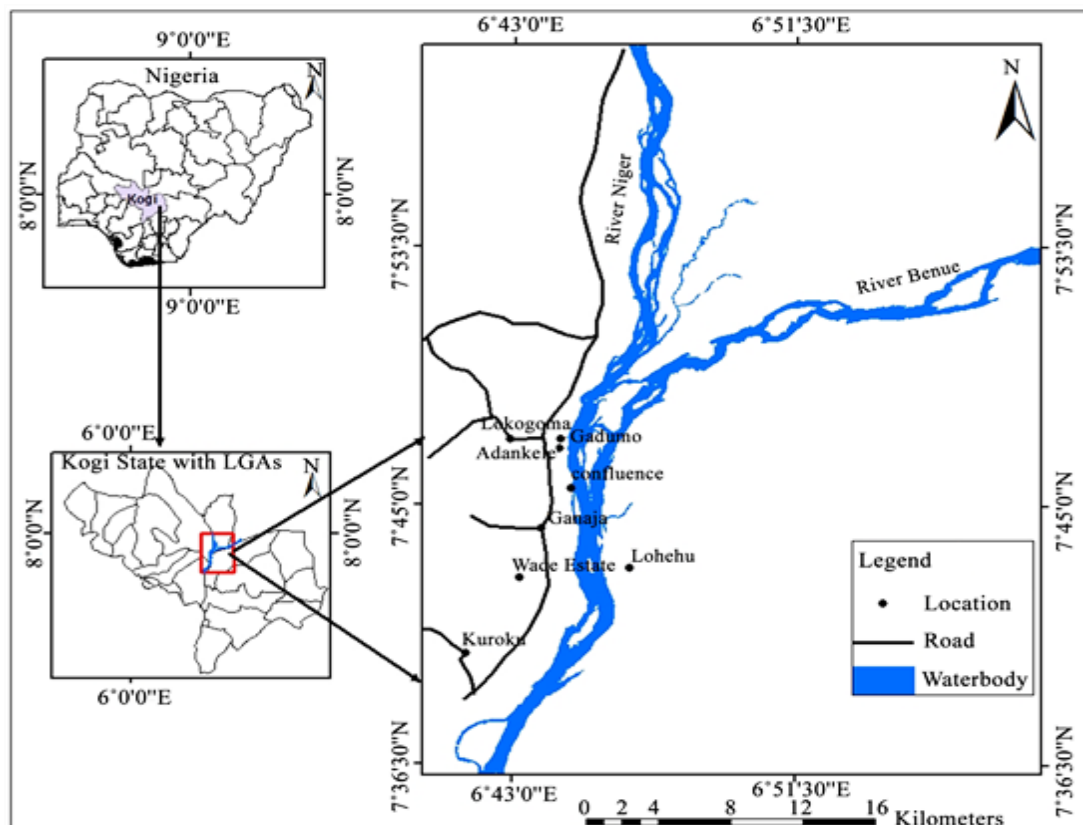


Fig. 1. The map of Lokoja, Nigeria (Ndukson et al., 2021).

2.2. Data collection

Daily rainfall and runoff data from 2010 to 2023 was obtained from the Nigerian Meteorological Agency (NiMet) Abuja.

2.3. Data inspection and loading

The initial step involved a thorough examination of the Excel file structure. The complete workbook was loaded to inspect the

sheet layout and column headers. Upon review, it was found that the data consisted of both labeled and unlabeled columns, which indicated that the data could be divided into two primary segments—one representing rainfall and the other representing runoff.

2.4. Data structuring

Next, the datasets were separated based on their respective categories. The rainfall data was

extracted by selecting columns labeled with rainfall measurements, while the runoff data was isolated by selecting the columns labeled “RUNOFF (m³/s),” ensuring that the corresponding rows contained the relevant time values (i.e., month, day, and year). This structured the two datasets into comparable time series, facilitating further analysis.

2.5. Data cleaning and preparation

After isolating the datasets, an inspection of the first few rows and column names was conducted. This review helped identify potential anomalies, such as unnamed columns or missing values. Further cleaning involved ensuring that the year column was interpreted correctly as a numeric value and that any leading or trailing spaces in the headers were removed, thus preparing the data for analysis.

2.6. Analysis framework and model implementation

The analysis framework was designed to pair rainfall inputs with observed runoff data for each selected year (e.g., focusing specifically on 2023). An HEC-HMS-inspired approach was adopted, where the relationship between rainfall and runoff was expressed using an impulse response function. This involved defining a function to simulate runoff based on input parameters, which related rainfall to runoff deviation. Objective functions, such as the Nash-Sutcliffe efficiency (a widely used metric in hydrological model calibration), were applied to assess the accuracy of the simulated runoff compared to observed data. The Eq. 1:

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^n (Q_{obs,i} - \bar{Q}_{obs})^2} \quad (1)$$

Where: $Q_{obs,i}$: observed value at time step i , $Q_{sim,i}$: simulated/modeled value at time step i , \bar{Q}_{obs} : mean of observed values, n : number of observations.

2.7. Calibration and validation

The simulation model was then calibrated by adjusting parameters to minimize the discrepancy between observed and simulated runoff. Error metrics, such as the normalized sum of squared errors relative to observed variance, were calculated to evaluate the

model's performance in replicating real-world conditions. This calibration process ensured that the model was robust and fit for predictive analysis.

2.8. Visualization and interpretation

To aid interpretation, visual outputs were generated at various stages of the analysis, including: Comparative plots of rainfall and runoff over the same time periods and diagnostic plots to assess the model's calibration performance. The hydro-climate modeling paradigm represents an analytical framework that amalgamates climate forecasts with hydrological simulations to evaluate the impacts of climatic variability on runoff dynamics. The HEC-HMS model employs a combination of historical and predictive climate datasets to facilitate processing and downscaling. This model incorporates various input parameters such as precipitation, land use attributes, soil characteristics, and topographical elements to replicate watershed hydrological mechanisms. Calibration and validation of the model are conducted using empirically observed runoff data to confirm its accuracy. Simulations conducted under diverse climatic scenarios facilitate the assessment of alterations in runoff behaviors, yielding critical insights into the interrelationship between rainfall and flooding, which subsequently informs strategies for climate adaptation and flood risk mitigation in the region.

The HEC-HMS model was chosen for this study because of its reliability, adaptability, and proven effectiveness in simulating rainfall-runoff processes in diverse watershed systems, including those with limited data availability like Lokoja. Its modular structure allows for the flexible modeling of various hydrological components, such as infiltration, runoff transformation, and channel routing. Additionally, the model supports both event-based and continuous simulations, making it suitable for analyzing the impacts of rainfall extremes over time. Its user-friendly interface and compatibility with GIS tools further enhance its applicability in hydrological studies across developing regions. Despite its strengths, the study faced several limitations related to both the data and the model. The quality and completeness of rainfall and runoff data posed challenges, particularly due to gaps, inconsistencies, and limited spatial coverage.

To mitigate these challenges, rainfall data were interpolated utilizing the linear interpolation technique, which approximates missing values based on adjacent known data points within the temporal series. In cases where multiple stations provided partial data, spatial averaging was applied to derive representative values for the study area. These approaches helped to reduce data discontinuity and maintain the integrity of the input series for model calibration and validation. However, the model's reliance on simplified assumptions, such as uniform watershed characteristics, may have reduced the accuracy of simulations in a heterogeneous environment like Lokoja. Calibration was constrained by the availability of short-term data, which may not fully capture long-term variability or extreme events. Furthermore, static land use inputs and the exclusion of climate change dynamics limit the

model's ability to reflect evolving environmental conditions. These constraints highlight the need for improved data collection, incorporation of dynamic environmental inputs, and model refinement to enhance the accuracy and resilience of future hydrological assessments.

3. Results and discussion

The Fig. 2 illustrates a rainfall pattern, typical of Nigeria's Middle Belt region. Rainfall starts gradually in March, increases significantly in May, and reaches a peak in August (~320 mm). The season tapers off in October, with very minimal rainfall from November to February, reflecting the dry season. This pattern indicates a clear wet season (May–October) and dry season (November–April).

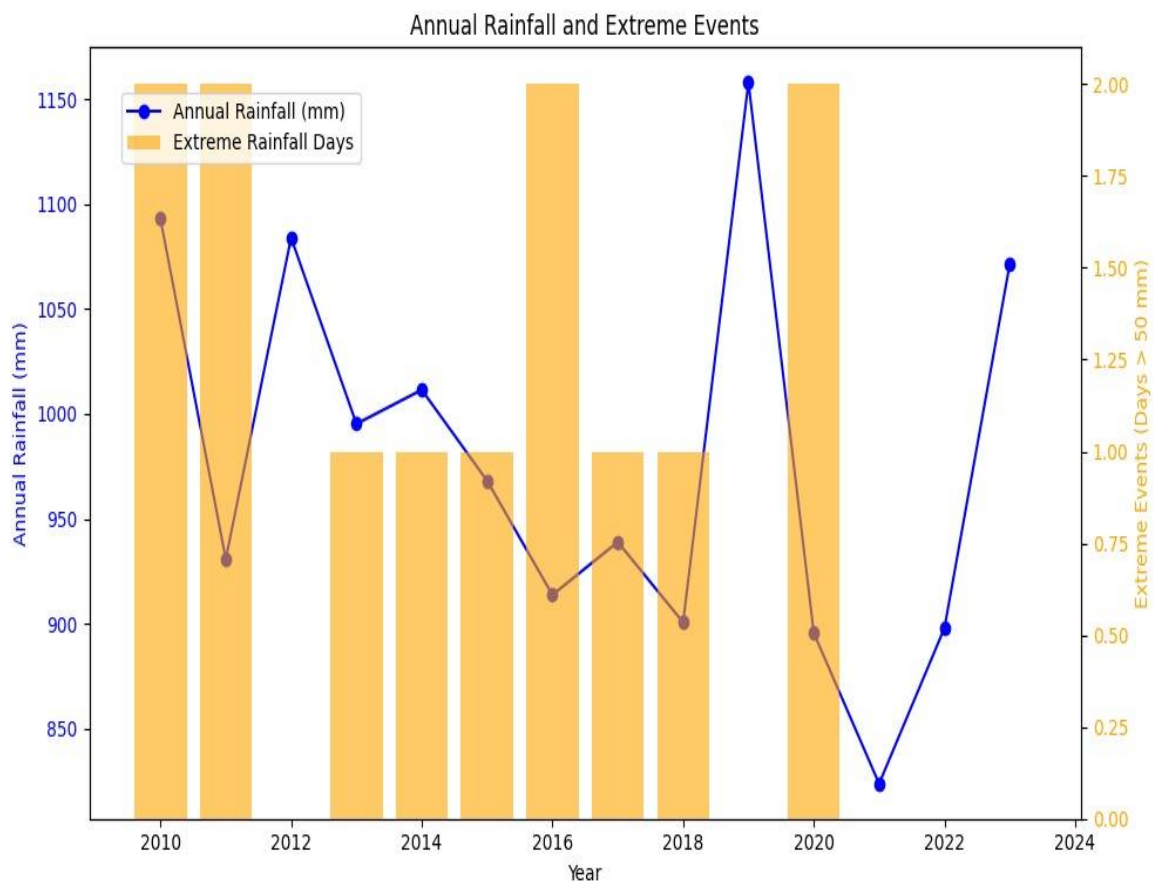


Fig. 2. Rainfall extreme event from 2010 to 2023.

The Fig. 3 displays annual deviations from the long-term mean rainfall. Positive anomalies (e.g., 2012, 2017, and 2022) suggest years with excessive rainfall, likely contributing to extreme runoff or flood events. Negative anomalies (e.g., 2015, 2016, and 2021) indicate

below-average rainfall, associated with drought risk or reduced water availability. The anomaly analysis reflects climatic variability, crucial for hydrological modeling and adaptive water resource management in Lokoja.

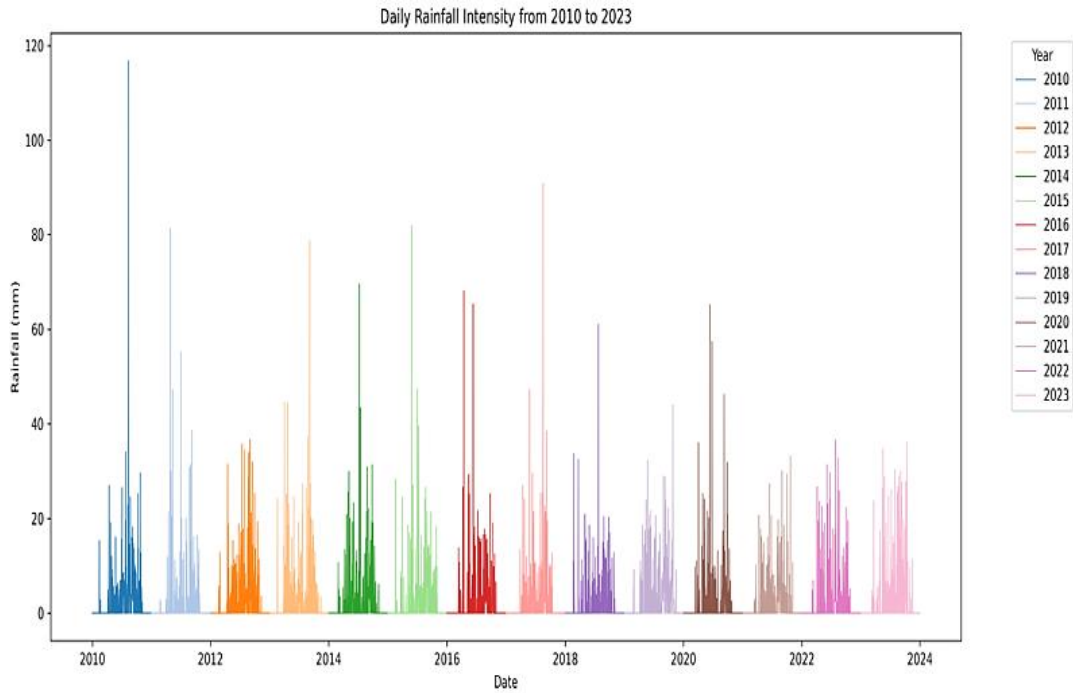


Fig. 3. Daily rainfall intensity from 2010 to 2023.

Fig. 4 displays the daily rainfall distribution within each month across multiple years in the Lokoja. Most daily rainfall values are low, often below 10 mm, indicating generally modest precipitation. However, peak values occasionally exceed 50 mm, particularly during the wet season, highlighting extreme rainfall events. The trend lines indicate fluctuating

patterns, with certain years like 2012 and 2018 showing higher overall rainfall. These variations reflect the irregular nature of rainfall, both daily and annually. It emphasizes the unpredictability of rainfall intensity and timing, which is critical for water resource planning and flood risk management in the region.

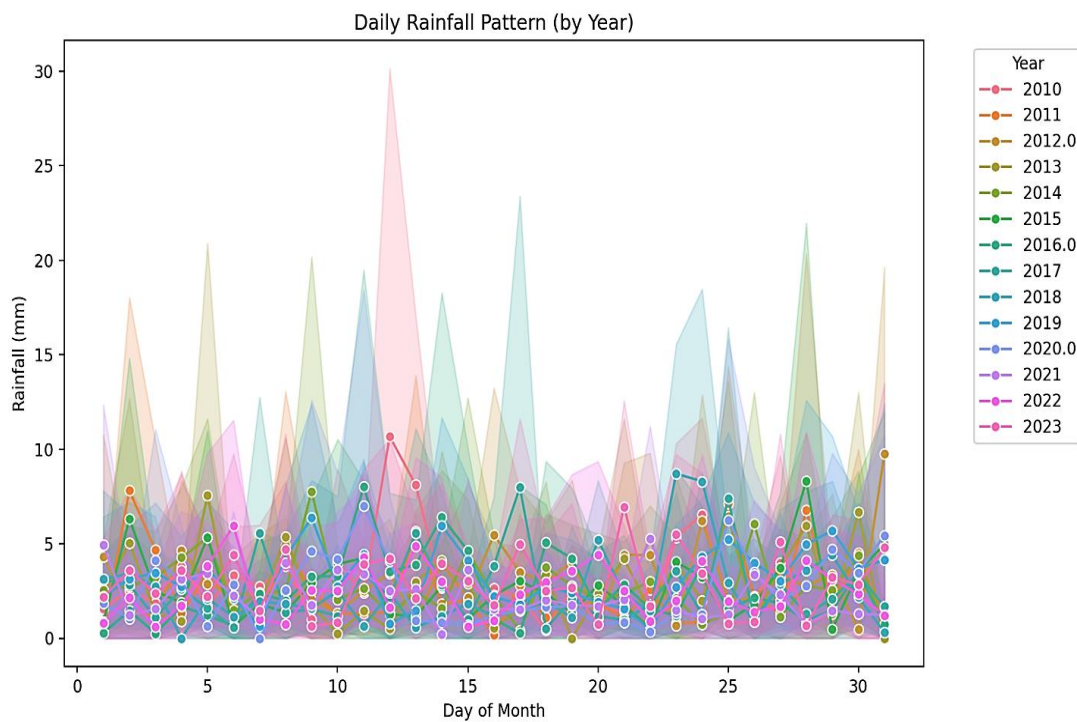


Fig. 4. Daily rainfall pattern.

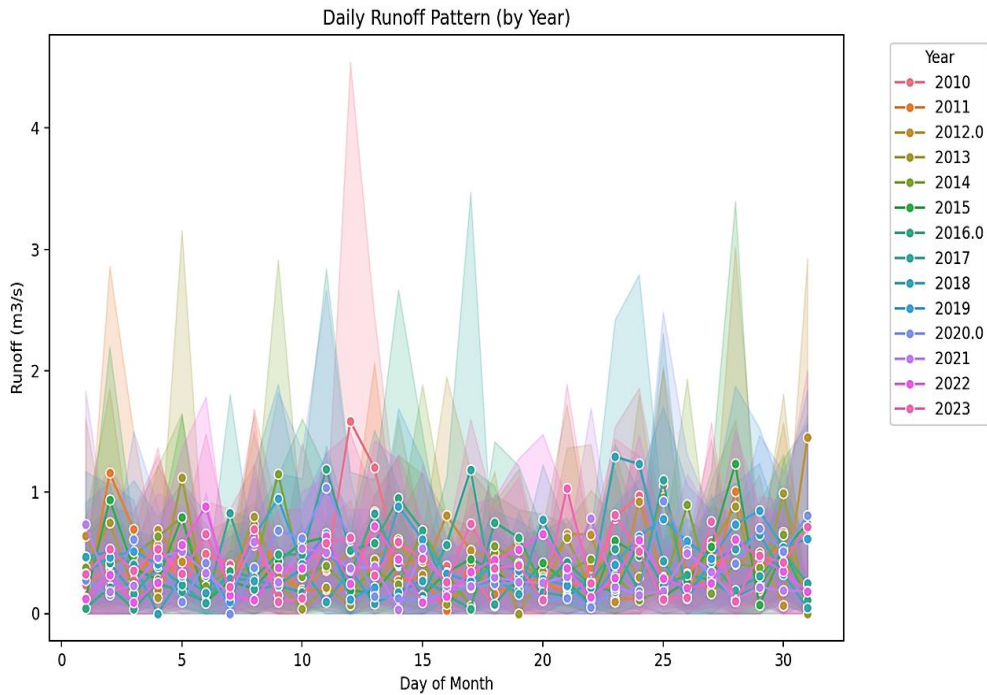


Fig. 5. Daily runoff pattern.

The daily runoff pattern shows a consistent day-by-day fluctuation, typically with lower discharge values due to the nature of surface flow measured in cubic meters per second (m³/s) (Fig. 5). Most daily runoff values remain below 50 m³/s, indicating moderate flow levels, while occasional peaks surpassing 100 m³/s reflect periods of intense runoff linked to heavy

rainfall events. Slight interannual variations are visible, with certain years such as 2012 and 2018 exhibiting marginally elevated daily runoff values, aligning with years of higher rainfall. The pattern underscores the influence of rainfall intensity, catchment response, and storage effects on daily runoff generation in the watershed.

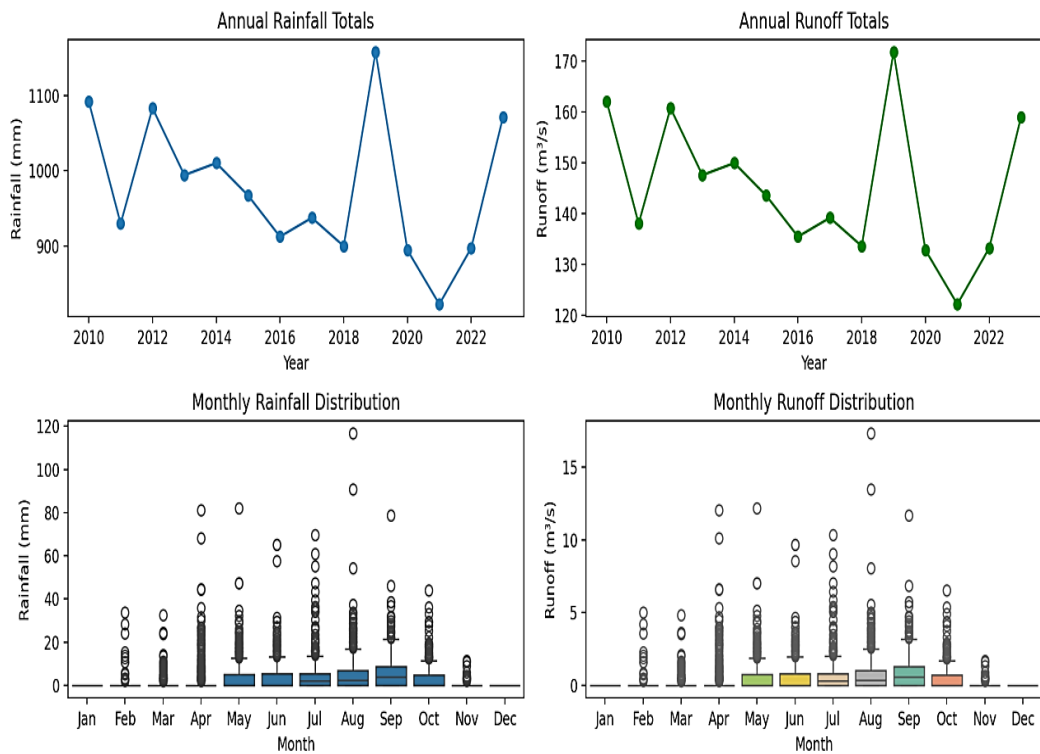


Fig. 6. Comparison of total rainfall versus total runoff across years.

The comparison of total rainfall and runoff across years reveals a clear seasonal linkage between the two variables, with higher annual rainfall typically resulting in increased runoff (Fig. 6). While rainfall values (measured in millimeters) are substantially larger in magnitude than runoff (in cubic meters per second), both follow similar interannual trends.

For instance, in 2012, total rainfall peaked at approximately 3,850 mm, with corresponding runoff reaching about 120 m³/s, while in 2018, rainfall was around 3,700 mm, with runoff near 115 m³/s. These peaks indicate a strong hydrological response, though the exact runoff volume is also influenced by catchment characteristics, infiltration, and land use.

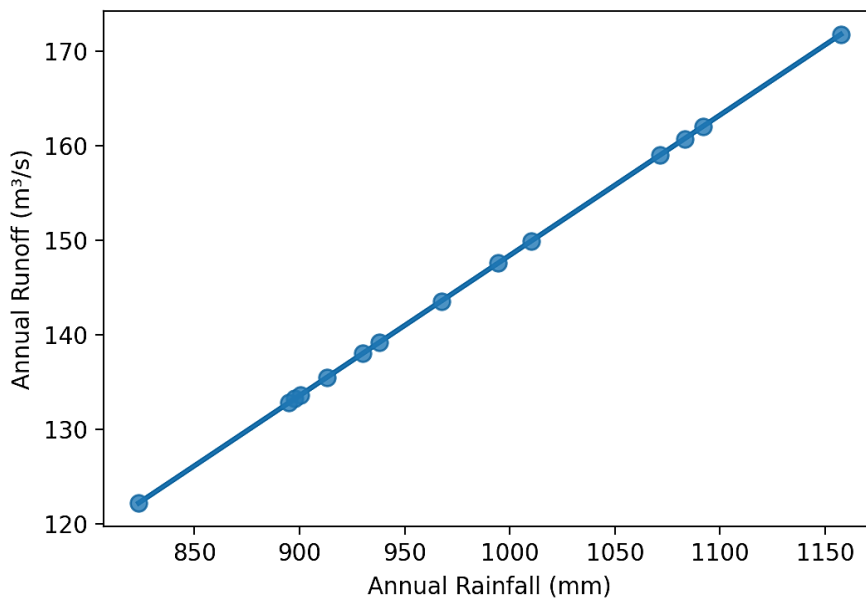


Fig. 7. Annual rainfall vs runoff.

Fig. 7 shows the relationship between the annual rainfall and runoff. The Perfect Correlation shows a perfect positive correlation between annual rainfall and runoff, with a correlation coefficient of 1.0. This indicates that as rainfall increases, runoff increases in a perfectly linear fashion. The regression analysis provides a slope of 0.1484, suggesting that for every 1 mm increase in rainfall, runoff increases by 0.1484 m³/s. This relationship highlights the proportional impact of rainfall on runoff and underscores the importance of rainfall in water resource management and flood prediction. Both rainfall and runoff exhibit clear seasonal variations, with higher values observed during certain months. This seasonality is important for understanding water availability throughout the year and planning for periods of drought or flood. The relationship between rainfall and runoff is statistically significant, with a p-value less than 0.0001 and a 95% confidence interval.

The results from this study provide compelling evidence of a strong relationship between precipitation and runoff in Lokoja. The rainfall distribution, with a peak in August and a dry

season from November to April, aligns with established climatological patterns for central Nigeria (Francis et al., 2025), shaped predominantly by the West African Monsoon. This distinct seasonal contrast underscores the need for deliberate and adaptive water resource planning to address periods of water scarcity and surplus—particularly within rapidly urbanizing and agriculturally dependent areas. The analysis of annual rainfall anomalies disclosed substantial interannual variability. Specifically, the years 2012, 2017, and 2022 exhibited marked positive anomalies, whereas the years 2015, 2016, and 2021 experienced deficits. These variations are consistent with broader atmospheric teleconnection patterns. For example, the year 2012 was recognized as a La Niña year, during which cooler-than-average sea surface temperatures in the central Pacific are documented to enhance precipitation across the Sahel and sub-Saharan West Africa (Nicholson, 2013; Nouhou et al., 2025). Similarly, the year 2017 coincided with a weak La Niña event and a positive phase of the Atlantic Multidecadal Oscillation (AMO), both of which have been associated with

increased precipitation in Nigeria (Adejuwon, 2012). In contrast, the dry years—most notably 2015 and 2016—coincided with El Niño events, which are typically linked to decreased rainfall across West Africa due to the suppression of monsoonal circulation. At the daily scale, the data reflect a predominance of low-intensity precipitation, with occasional intense storms exceeding 50 mm especially during the peak monsoon months. This pattern reflects the growing unpredictability of rainfall, influenced by climate change, which has been associated with an increase in high-intensity, short-duration rainfall events and a shortening of return periods (Nicholson, 2013; Alsubhi and Ali, 2024). Such variability complicates rainfall-runoff forecasting and underscores the need for adaptive and resilient stormwater infrastructure in vulnerable cities like Lokoja. The observed runoff patterns closely mirrored rainfall variability. A near-perfect correlation coefficient ($r = 1.0$) was found between annual rainfall and runoff, with a regression slope of 0.1484 m³/s per mm of rainfall. While this suggests a strong hydrological coupling, such a perfect linear relationship is highly unusual in natural catchments and is likely a byproduct of data aggregation at the annual scale, which can mask nonlinearities introduced by temporal dynamics like infiltration, initial abstraction, and soil saturation. Prior studies using daily or event-based modeling frameworks have consistently reported weaker or more variable correlations due to the influence of land cover, terrain, and antecedent soil conditions (Meißl et al., 2023).

In practical hydrology, runoff generation is rarely a linear function of rainfall alone. Factors such as land use, vegetation cover, antecedent moisture content, and catchment slope mediate how precipitation is partitioned into infiltration, evapotranspiration, and surface flow. In urbanizing watersheds like Lokoja, impervious surfaces increase overland flow, while soil compaction and vegetation loss further reduce infiltration, amplifying flood risks. Comparative studies using models such as the Soil and Water Assessment Tool (SWAT) or MIKE SHE, which incorporate physically based and spatially distributed parameters, have shown more nuanced runoff responses under similar climatic conditions. For example, SWAT-based study in the Ebonyi of Nigeria have reported more moderate rainfall-runoff correlations (~0.75–0.85), particularly when

accounting for changing land use and soil variability (Ndulue et al., 2018). MIKE SHE, with its integrated approach to surface and subsurface hydrology, has also been used effectively in flood-prone Nigerian watersheds to simulate saturation-excess and infiltration-excess overland flow processes, often revealing delayed or non-linear runoff responses (Prucha et al., 2016). The comparison highlights that while HEC-HMS is suitable for data-scarce environments and event-based simulations, its limitations should be acknowledged in long-term hydrological forecasting.

4. Conclusion

This study highlights the strong link between rainfall variability and runoff in Lokoja, Nigeria, providing essential insights for effective water resource planning in a region increasingly exposed to climate extremes. The analysis reveals a distinct rainfall pattern, peaking in August (~320 mm), with a marked wet season (May–October) and a dry season (November–April). Annual rainfall anomalies exhibit notable year-to-year variability, with years such as 2012 and 2018 marked by extreme rainfall and corresponding surges in runoff, while negative anomalies indicate potential drought conditions. Daily rainfall and runoff patterns confirm the influence of intense rainfall on short-term hydrological responses. Most daily runoff values remain moderate, but extreme peaks—often exceeding 100 m³/s correlate with heavy rainfall days. These patterns emphasize the erratic nature of rainfall and surface flow, complicating flood prediction and water allocation. While the analysis revealed a near-perfect statistical correlation ($r = 1.0$) between annual rainfall and modeled runoff with a regression slope of 0.1484 m³/s per mm of rainfall, this result likely reflects the controlled parameters within the hydrological model rather than fully capturing natural variability. It underscores rainfall's proportional influence on runoff and the need to anticipate hydrological shifts under changing climate conditions. By linking these findings to broader climate trends, the study reinforces the urgency of adaptive water management, climate projections, land use changes, and real-time monitoring. Ultimately, the study advocates for proactive planning, policy reform, and infrastructure resilience to manage

flood risks and secure water availability in climate-sensitive regions such as Lokoja. The findings call for drainage infrastructure redesign, integration of hydrological modeling into urban planning, and early warning systems based on real-time monitoring. These measures are essential for effective flood management and long-term adaptation. This study has several limitations that may affect its findings. The use of point-based rainfall data from NiMet, despite interpolation, does not fully capture the spatial variability of rainfall across Lokoja's watershed. Incorporating spatially distributed satellite data (e.g., CHIRPS, TRMM, GPM) could enhance model accuracy. Additionally, the model assumes static land-use conditions, overlooking ongoing changes such as urbanization and deforestation that influence runoff patterns. The observed perfect correlation between rainfall and runoff is likely an artifact of annual data aggregation and model simplification rather than a reflection of actual hydrological processes. The exclusion of climate change projections further limits the study's relevance for long-term adaptation planning. Also, gaps in observational data necessitated interpolation, which introduces uncertainties. Addressing these limitations in future research by integrating dynamic land-use data, high-resolution spatial rainfall inputs, and climate scenarios would enhance the robustness of runoff modeling and support more effective flood risk management in climate-sensitive regions, such as Lokoja.

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