
INTEGRATED HEC-HMS AND IMPROVED SOIL MOISTURE BALANCE MODELLING FOR GROUNDWATER RECHARGE ASSESSMENT IN THE SEMI-ARID SOKOTO BASIN, NIGERIA

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DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

Groundwater is the principal source of freshwater for domestic, agricultural and livestock activities in the semi-arid Sokoto Basin of northwestern Nigeria, yet increasing water demand, climate variability and uncertainty in aquifer replenishment pose growing challenges to its sustainable management. This study developed an integrated Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) and Improved Soil Moisture Balance (SMB) framework for estimating groundwater recharge using long-term hydro-meteorological records from 1990 to 2025, observed streamflow, measured soil hydraulic properties and topographic information. HEC-HMS was used to simulate rainfall–runoff processes, while the Improved SMB model incorporated dynamic root-zone soil moisture accounting, spatially variable soil hydraulic properties, moisture-dependent evapotranspiration, separate treatment of lateral runoff and threshold-controlled deep percolation. Model calibration produced a Nash–Sutcliffe Efficiency (NSE) of 0.84, coefficient of determination (R^2) of 0.86, Root Mean Square Error (RMSE) of 42.6 m³/s and Percent Bias (PBIAS) of +3.7%. Independent validation yielded NSE = 0.77, R^2 = 0.79, RMSE = 49.8 m³/s and PBIAS = −4.2%, demonstrating satisfactory predictive performance. Long-term recharge analysis showed pronounced interannual variability, with a mean annual recharge of 126 mm/year, a minimum of 62 mm/year in 1991 and a maximum of 205 mm/year in 2009. Rainfall and recharge were positively correlated (r = 0.72; R^2 = 0.52), with a regression slope of 0.115 mm recharge per millimetre of rainfall and an intercept of −34.3 mm, indicating threshold-controlled recharge under semi-arid conditions. Spatial analysis further identified distinct recharge zones controlled by rainfall, soil hydraulic characteristics and terrain conditions. The integrated framework provides a reproducible decision-support approach for groundwater planning, managed aquifer recharge, watershed conservation and climate-resilient water-resource management in semi-arid regions.

Keywords: groundwater recharge; hec-hms; hydrological modelling; semi-arid hydrology; soil moisture balance

1. INTRODUCTION

Groundwater is a critical component of global freshwater resources and supports domestic water supply, irrigated agriculture, industrial production and ecosystem functioning. Its importance is particularly pronounced in regions where surface-water availability is strongly seasonal or unreliable. Unlike surface reservoirs and rivers, groundwater is less directly exposed to evaporation and can provide an important buffer against short-term rainfall variability and drought (Freeze & Cherry, 1979; de Vries & Simmers, 2002). Consequently, sustainable groundwater development has become increasingly important as population growth, urbanisation, agricultural expansion and industrial development increase freshwater demand worldwide (Scanlon et al., 2006).

Recent global assessments further demonstrate the importance of groundwater within an increasingly variable hydrological system. The World Meteorological Organization (WMO, 2023) reported substantial regional anomalies in river discharge, reservoir inflows, soil moisture and groundwater conditions during 2022, reflecting increasing hydrological variability across many regions. Similarly, the United Nations World Water Development Report emphasises that water security is closely connected to economic development, food production, social stability and resilience to climatic extremes (UNESCO, 2024). These assessments highlight the need for improved quantitative understanding of groundwater replenishment, particularly in regions where groundwater constitutes a major component of freshwater supply.

Despite its importance, groundwater is under increasing pressure from abstraction, land-use change, climatic variability and changes in natural recharge. Excessive groundwater withdrawal relative to aquifer replenishment can result in declining groundwater levels, reduced baseflow, increasing pumping costs and deterioration of groundwater-dependent ecosystems (Taylor et al., 2013). The sustainability of groundwater development therefore depends not only on the volume of groundwater stored within an aquifer but also on the rate and variability of groundwater recharge.

Groundwater recharge is the downward movement of infiltrated water through the unsaturated zone to the saturated aquifer. It is among the most difficult components of the hydrological cycle to quantify because it depends on interacting climatic, hydrological, soil, geological, vegetation and topographic controls (Healy, 2010). Recharge can vary considerably over both space and time, and the magnitude of this variability becomes particularly important when groundwater-development decisions are based on long-term average estimates (Scanlon et al., 2006). Reliable estimation of recharge is therefore essential for groundwater-resource assessment, sustainable abstraction planning, aquifer protection and climate-resilient water management.

The difficulty of recharge estimation is particularly pronounced in semi-arid environments. Rainfall in such regions is strongly seasonal and frequently occurs as short-duration, high-intensity storms, while potential evapotranspiration remains high for much of the year. Consequently, a large proportion of precipitation may be lost through evapotranspiration and surface runoff before sufficient soil moisture is accumulated to generate deep percolation (Healy, 2010). Groundwater recharge therefore tends to be episodic and threshold-dependent rather than continuous. Scanlon et al. (2006) demonstrated that recharge in arid and semi-arid environments can vary substantially in response to rainfall magnitude, soil characteristics and land-surface conditions, while Taylor et al. (2013) showed that intense rainfall events can play a disproportionate role in groundwater replenishment across parts of Africa.

Northern Nigeria exhibits many of these characteristics. The Sokoto Basin forms the Nigerian sector of the larger transboundary Iullemmeden Basin shared principally between Nigeria and the Republic of Niger. Within Nigeria, the basin extends across Sokoto and Kebbi States and parts of Zamfara and Niger States. The broader hydrogeological system extends beyond the Nigerian boundary into Niger Republic; however, the hydrological modelling undertaken in this study is restricted to the delineated Nigerian model domain represented in Figure 1. This distinction is important because the hydrogeological basin is transboundary, whereas the quantitative recharge estimates presented in this study relate specifically to the modelled catchment.

Groundwater is extensively used within the Sokoto Basin for domestic water supply, irrigation, livestock production and rural livelihoods. However, recurrent drought, agricultural expansion, population growth and high rainfall variability place increasing pressure on available groundwater resources. Reliable information on recharge remains limited because of sparse hydrological observations, inadequate long-term groundwater monitoring and the complexity of rainfall–runoff–infiltration interactions. Consequently, groundwater-development decisions may be undertaken without sufficient quantitative information on the temporal and spatial variability of aquifer replenishment.

Numerous methods have been developed for estimating groundwater recharge, including empirical rainfall–recharge relationships, water-table fluctuation methods, chloride mass balance, lysimeter measurements, environmental tracers, water-balance techniques and physically based numerical models (Scanlon et al., 2002; Healy, 2010). Each method has advantages and limitations. Field-based approaches may provide detailed information at individual locations but can require extensive monitoring and may not adequately represent basin-scale spatial variability. Conversely, empirical approaches are comparatively simple to implement but may not adequately represent changing hydrological conditions. Sophocleous (2004) noted that recharge estimation remains a major source of uncertainty in groundwater assessment because no single technique can completely represent the complexity of natural recharge processes.

These limitations are especially important in African basins where observational networks may be sparse and long-term hydrogeological data are frequently incomplete. Xu and Beekman (2019) emphasised that groundwater-recharge assessment in Africa requires approaches capable of integrating available climatic, hydrological and hydrogeological information while explicitly recognising data limitations and spatial variability. An integrated modelling framework can therefore provide a useful

alternative by combining complementary techniques rather than depending on a single recharge-estimation method.

The Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) provides a widely applied framework for simulating rainfall–runoff processes at catchment scale. It allows precipitation losses, runoff transformation and channel routing to be represented using established hydrological methods. Soil Moisture Balance (SMB) modelling, in contrast, provides a physically interpretable framework for tracking rainfall inputs, evapotranspiration losses, runoff, soil-water storage and drainage below the root zone. Integration of the two approaches enables runoff estimated by a calibrated hydrological model to be incorporated directly into soil-water accounting, thereby reducing reliance on assumed runoff coefficients.

However, a conventional SMB formulation based solely on annual or monthly precipitation minus evapotranspiration and runoff can oversimplify recharge generation in semi-arid environments. Recharge generally occurs only after antecedent soil-water deficits have been replenished and soil storage exceeds a drainage threshold. Soil depth, field capacity, wilting point and saturated hydraulic conductivity also vary spatially, while evapotranspiration becomes constrained as soil moisture declines. These processes require a temporally explicit soil-water accounting framework rather than simple residual water-balance estimation.

Accordingly, the present study integrates HEC-HMS with an Improved SMB model incorporating dynamic root-zone moisture accounting, variable soil hydraulic properties, moisture-dependent evapotranspiration, explicit treatment of runoff and lateral losses, and threshold-controlled deep percolation. The integrated approach is consistent with the broader need for groundwater assessments that account for interactions among surface hydrology, soil-water processes and groundwater replenishment (Gleeson et al., 2020; Xu & Beekman, 2019).

The aim of this study is therefore to develop and apply an integrated HEC-HMS–Improved SMB framework for assessing the temporal and spatial variability of groundwater recharge in the semi-arid Sokoto Basin. Specifically, the study uses long-term hydro-meteorological observations from 1990 to 2025, observed streamflow, soil hydraulic measurements and topographic information to simulate rainfall–runoff processes, quantify groundwater recharge, examine the rainfall–recharge relationship and identify spatial variations in recharge potential.

Beyond its hydrological contribution, the framework is intended as an engineering decision-support tool. Quantitative recharge information can support the siting of managed aquifer recharge facilities, groundwater-development planning, watershed conservation, drought-risk management and prioritisation of areas for groundwater protection. The approach therefore connects hydrological modelling with practical engineering innovation and evidence-based water policy, supporting sustainable water-resource development and improved climate resilience in northern Nigeria and comparable semi-arid environments.

2. MATERIALS AND METHODS

The study was conducted in the Sokoto Basin in northwestern Nigeria, which forms the Nigerian sector of the larger transboundary Iullemmeden Basin extending into the Republic of Niger. Within Nigeria, the basin covers Sokoto and Kebbi States and parts of Zamfara and Niger States. Although the broader hydrogeological system is transboundary, the numerical modelling undertaken in this study was restricted to the Nigerian catchment delineated from the Digital Elevation Model (DEM) and represented in Figure 1. The delineated HEC-HMS model domain covers approximately **28,400 km²** and should therefore not be interpreted as the total geographical area of the entire Sokoto-Rima or transboundary Iullemmeden Basin.

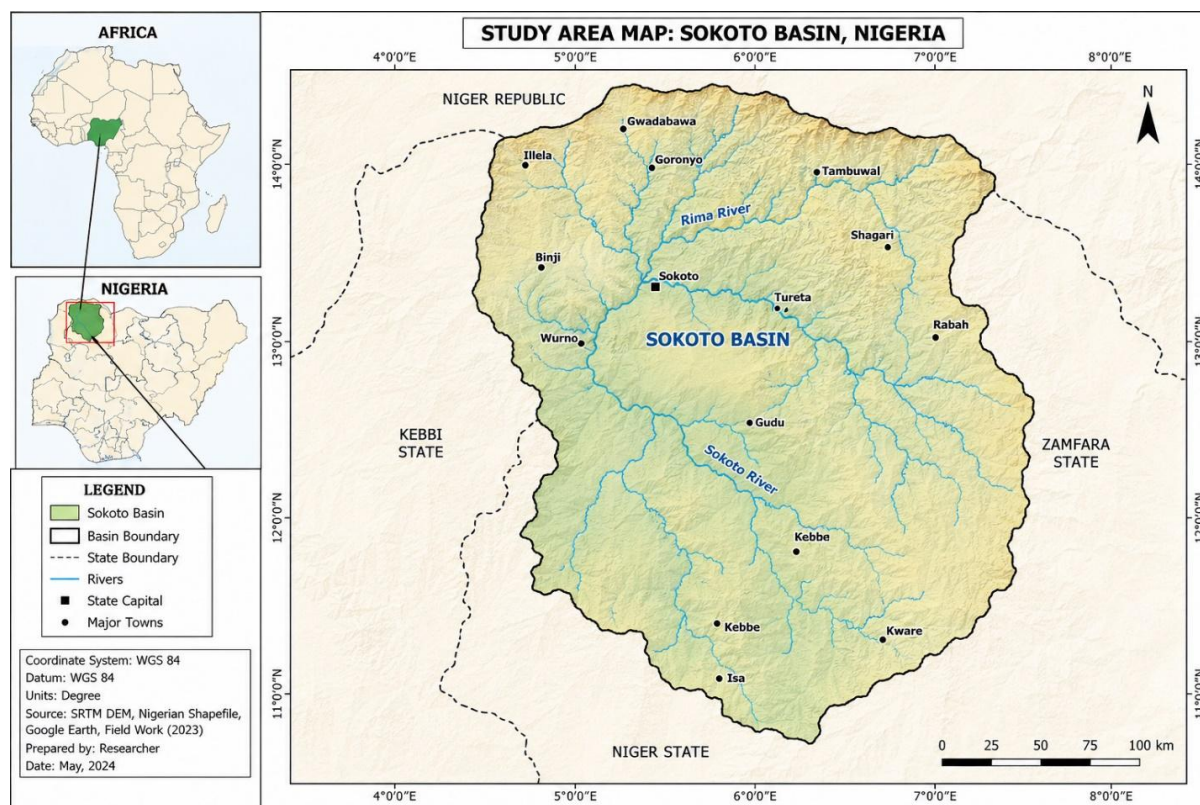


Figure 1: Study Area Map of the Sokoto Basin

Geologically, the basin consists predominantly of sedimentary formations, including the Gundumi, Rima, Sokoto and Gwandu Formations, which exhibit differences in lithology, aquifer properties and groundwater-storage characteristics. These formations constitute important groundwater-bearing units supporting domestic water supply, irrigation and livestock production within the region.

The climate is semi-arid and characterized by a distinct wet season extending approximately from May to October and a prolonged dry season from November to April. Annual rainfall generally ranges between 700 and 1,200 mm, with most precipitation occurring between June and September. Mean annual temperatures commonly exceed 30°C, resulting in substantial atmospheric water demand and high evapotranspiration losses. The drainage system is dominated by the Sokoto-Rima River network.

Soils within the modelled area are predominantly sandy loam and loamy sand, with localized sandy clay loam and finer-textured deposits. Variations in soil texture influence infiltration, soil-water retention, runoff generation and the amount of water available for deep percolation. Land use is dominated by rain-fed and irrigated agriculture, grazing land, riparian vegetation and settlements. The combined effects of climate, soils, terrain and land use produce considerable spatial and temporal variability in runoff and groundwater recharge.

2.2 Overall Modelling Framework

The methodological framework integrated HEC-HMS rainfall-runoff simulation with an Improved Soil Moisture Balance (SMB) model. The modelling procedure consisted of five principal stages: (1) hydro-meteorological, soil and spatial data preparation; (2) DEM-based watershed delineation and HEC-HMS model development; (3) calibration and validation of simulated runoff against observed streamflow; (4) daily root-zone soil-water accounting and estimation of deep percolation using the Improved SMB model; and (5) temporal and spatial analysis of groundwater recharge.

The principal rationale for coupling the two models was to avoid estimating runoff as an arbitrary residual or fixed fraction of rainfall within the SMB calculation. Instead, surface runoff was independently simulated using the calibrated HEC-HMS model and subsequently transferred to the

SMB framework. The SMB component then accounted for rainfall, evapotranspiration, soil-water storage, lateral losses and threshold-controlled drainage below the root zone.

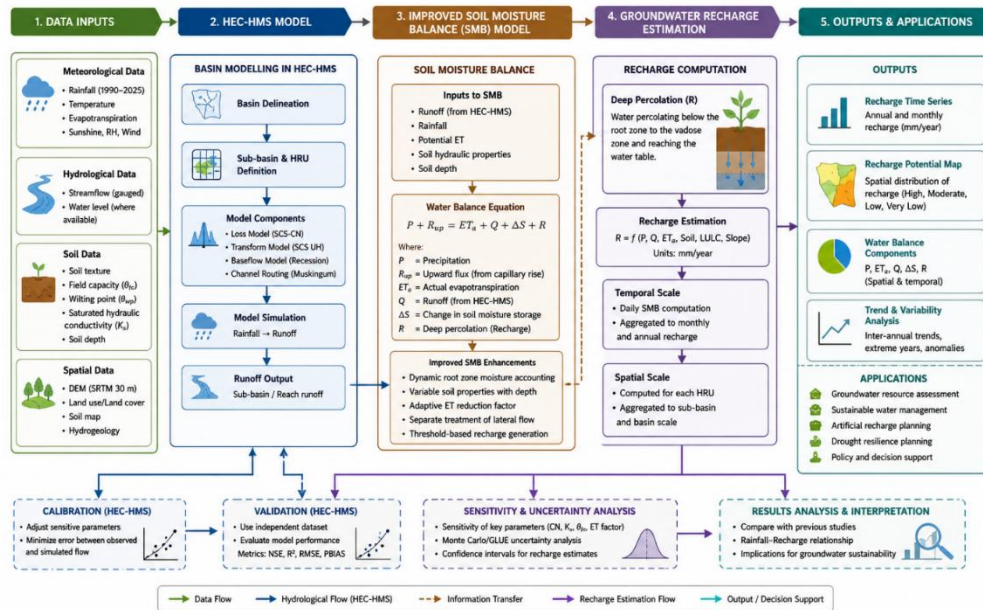


Figure 2: Integrated HEC-HMS-SMB Methodological Framework

2.3 Data Collection and Preparation

Meteorological, hydrological, soil and topographic datasets were assembled for development of the integrated framework. Daily rainfall and temperature records covering 1990–2025 were obtained from the Nigerian Meteorological Agency (NiMet). Relative humidity and wind-speed observations were also incorporated into the climatic dataset for evapotranspiration estimation.

Observed daily streamflow records from hydrological gauging stations within the modelled basin were used for HEC-HMS calibration and validation. The streamflow record used in the modelling was divided into 1990–2011 for calibration and 2012–2025 for validation, consistent with the periods represented in the observed-versus-simulated hydrograph.

Soil samples collected during the 2024 field investigation were analysed for soil texture, bulk density, field capacity, permanent wilting point and saturated hydraulic conductivity. These measurements were treated as static soil hydraulic parameters for the long-term simulation. This assumes that the principal soil hydraulic characteristics represented by the sampled locations remained sufficiently stable to characterize the corresponding soil units during the 1990–2025 simulation period. The assumption is necessary because equivalent historical measurements were unavailable and represents a limitation of the long-term reconstruction.

A 30-m Shuttle Radar Topography Mission (SRTM) DEM was used for catchment delineation, drainage-network extraction and terrain analysis. Land-use/land-cover information was obtained from Landsat imagery, while the FAO/Harmonized World Soil Database (HWSD) provided supplementary spatial soil information used to extend measured soil characteristics across the modelled area.

Table 1: Summary of Meteorological, Hydrological and Soil Datasets.

Dataset	Variable	Source	Temporal resolution	Spatial resolution	Period/status	Purpose
Meteorological	Rainfall	NiMet	Daily	Station	1990–2025	Hydrological forcing
Meteorological	Temperature	NiMet	Daily	Station	1990–2025	Evapotranspiration estimation
Meteorological	Relative humidity	NiMet	Daily	Station	1990–2025	Climate/ET analysis
Meteorological	Wind speed	NiMet	Daily	Station	1990–2025	Evapotranspiration estimation
Hydrological	Streamflow	NIHSA/River gauge stations	Daily	Gauge	1990–2025*	HEC-HMS calibration and validation
Soil	Texture	Field/laboratory analysis	Static	Sampling sites	Sampled 2024	Soil classification
Soil	Bulk density	Laboratory analysis	Static	Sampling sites	Sampled 2024	Soil-water parameterization
Soil	Field capacity	Laboratory analysis	Static	Sampling sites	Sampled 2024	Root-zone storage calculation
Soil	Permanent wilting point	Laboratory analysis	Static	Sampling sites	Sampled 2024	Available-water calculation
Soil	Saturated hydraulic conductivity	Laboratory analysis	Static	Sampling sites	Sampled 2024	Drainage/infiltration parameterization
Spatial	DEM	SRTM	Static	30 m	DEM product	Watershed and terrain delineation
Spatial	Land use/land cover	Landsat	Annual/periodic	30 m	2020–2025	Surface characteristics
Spatial	Soil map	FAO/HWSD	Static	250 m	Reference dataset	Spatial soil parameterization

The 1990–2025 streamflow period represents the record used to construct the calibration and validation datasets. Calibration covered 1990–2011 and validation covered 2012–2025.

Because the soil observations represent measurements made in 2024 rather than annual observations throughout the modelling period, the analysis assumes temporally invariant soil hydraulic properties. Consequently, long-term changes in soil structure arising from land management, erosion or other processes are not explicitly represented.

2.4 HEC-HMS Rainfall-Runoff Modelling

Rainfall-runoff simulation was undertaken using the Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS Version 4.12). Watershed boundaries, drainage networks and sub-basins were delineated from the SRTM DEM in a GIS environment and subsequently imported into HEC-HMS.

The Soil Conservation Service Curve Number (SCS-CN) method was used to represent rainfall losses because it provides a practical means of incorporating soil type, land use and antecedent moisture effects in data-limited catchments.

The potential maximum retention, (S) (mm), was computed from the Curve Number (CN) using Equation 1.

$$S = \frac{25400}{CN} - 254 \quad (1)$$

Where S is the maximum potential soil water retention (mm) and CN is the dimensionless Curve Number representing land use, soil type and antecedent moisture conditions.

Direct runoff depth, (Q) (mm), was then estimated using Equation 2.

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad (2)$$

Where Q is direct runoff (mm), P is rainfall depth (mm), (I_a) is initial abstraction (mm), commonly taken as (0.2 S), and S is potential maximum retention (mm).

Runoff transformation from rainfall excess to the catchment hydrograph was represented using the SCS Unit Hydrograph method. Channel flow was routed using the Muskingum method, with routing parameters (K) and (X) representing travel time and relative storage weighting, respectively.

The delineated watershed area used in HEC-HMS was approximately **28,400 km²**. This value represents the DEM-derived computational domain used for the present model and **not the total area of the complete Sokoto-Rima/Iullemmeden hydrological system**.

Table 2: Hydrological Model Parameters Used in HEC-HMS and Improved Soil Moisture Balance Simulation.

Component	Parameter	Symbol	Value	Unit
Basin	Watershed Area	A	28,400	km ²
Basin	Curve Number	CN	68–84	–
Basin	Initial Abstraction	Ia	12.6	mm
Basin	Lag Time	Tlag	5.4	hr
Basin	Time of Concentration	Tc	8.2	hr
Channel	Manning Roughness	n	0.035	–
Channel	Muskingum K	K	4.0	hr
Channel	Muskingum X	X	0.20	–
Soil	Field Capacity	θFC	0.28	m ³ /m ³
Soil	Wilting Point	θWP	0.14	m ³ /m ³
Soil	Saturated Moisture	θS	0.43	m ³ /m ³
Soil	Hydraulic Conductivity	Ks	18.5	mm h ⁻¹
SMB	Root Zone Depth	Zr	1.20	m
SMB	Deep Percolation Threshold	R	Variable	mm

2.5 HEC-HMS Calibration and Validation

HEC-HMS calibration was undertaken by adjusting hydrologically sensitive parameters within physically reasonable ranges until the simulated hydrograph reproduced the timing and magnitude of observed discharge. Particular attention was given to the Curve Number, initial abstraction, lag time and routing parameters because these control runoff volume, peak discharge and hydrograph timing.

The available discharge record was separated temporally to maintain independence between model calibration and validation. The 1990–2011 period was used for calibration, while 2012–2025 was reserved for validation. No further parameter optimisation was undertaken using the validation dataset.

Calibration and validation performance were evaluated using NSE, R², RMSE and PBIAS as described in Section 2.8. The calibrated HEC-HMS runoff series was subsequently supplied to the Improved SMB model as the surface-runoff component of the daily water balance.

2.6 Improved Soil Moisture Balance Model

Groundwater recharge was estimated using a daily Improved Soil Moisture Balance model coupled with HEC-HMS runoff. Unlike a simple residual water-balance calculation, the Improved SMB framework explicitly tracked the state of root-zone soil-water storage and allowed recharge to occur only when sufficient water was available after evapotranspiration, runoff and soil-moisture requirements had been satisfied.

The general daily root-zone water balance was represented in Equation 3.

$$R_t = S_t - S_{t-1} + P_t - Q_t - ET_{a,t} - L_t \quad (3)$$

Where S_t is root-zone soil-water storage at the end of day t (mm), S_{t-1} is storage from the preceding day (mm), P_t is daily precipitation (mm), Q_t is HEC-HMS simulated surface runoff (mm), $ET_{a,t}$ is actual evapotranspiration (mm), L_t represents lateral or other explicitly represented drainage losses (mm), and R_t is groundwater recharge or deep percolation below the root zone (mm).

Equivalently, the daily change in storage can be expressed in Equation 4.

$$\Delta S_t = P_t - Q_t - ET_{a,t} - L_t - R_t \quad (4)$$

This formulation ensures that recharge is calculated as part of a closed daily water balance rather than simply as (P-ET-Q) at annual scale.

2.6.1 Dynamic Root-Zone Moisture Accounting

The maximum root-zone water storage associated with field capacity was determined using Equation 5.

$$\begin{aligned} S_{FC} \\ = \theta_{FC} Z_r (1000) \end{aligned} \quad (5)$$

While storage corresponding to permanent wilting point expressed in Equation 6.

$$\begin{aligned} S_{WP} \\ = \theta_{WP} Z_r (1000) \end{aligned} \quad (6)$$

Where S_{FC} and S_{WP} are root-zone water storage at field capacity and wilting point (mm), respectively; θ_{FC} and θ_{WP} are volumetric field capacity and wilting-point water contents (m^3/m^3); and Z_r is effective root-zone depth (m).

The model updated S_t sequentially at the daily time step, thereby retaining the influence of antecedent moisture conditions. This is particularly important under semi-arid conditions because two rainfall events of equal magnitude may generate different recharge depending on the initial soil-water deficit.

2.6.2 Spatially Variable Soil Hydraulic Properties

Measured field capacity, wilting point and saturated hydraulic conductivity differed among the sampled soil units. Rather than representing the entire basin with a single homogeneous soil condition, the Improved SMB framework used the corresponding hydraulic characteristics to parameterize soil-water storage and drainage behaviour within the represented soil zones.

This modification allows areas characterized by sandy and highly conductive soils to drain differently from areas with greater water-retention capacity. The spatial variability of soil properties therefore influences both the amount of water retained within the root zone and the potential for deep percolation.

2.6.3 Moisture-Dependent Actual Evapotranspiration

Actual evapotranspiration was constrained by the amount of water available within the root zone. Under sufficiently wet conditions, evapotranspiration could approach the atmospheric demand represented by potential evapotranspiration. As soil moisture declined toward the permanent wilting point, evapotranspiration was progressively reduced using a soil-water stress factor expressed in Equation 7.

$$\begin{aligned} ET_{a,t} \\ = K_{s,t} ET_{p,t} \end{aligned} \quad (7)$$

Where $ET_{a,t}$ is actual evapotranspiration (mm/day), $ET_{p,t}$ is potential evapotranspiration (mm/day), and $K_{s,t}$ is the dimensionless soil-water stress coefficient bounded between 0 and 1.

For the root-zone accounting framework, $K_{s,t}$ was represented as a function of available soil water:

$$\min \left[1, \max \left(0, \frac{S_t - S_{WP}}{S_{FC} - S_{WP}} \right) \right] \quad (8)$$

Thus, K_s approaches 1 under adequately moist conditions and declines toward zero as storage approaches the permanent wilting-point threshold.

2.7 Threshold-Based Recharge and Lateral-Flow Treatment

The central improvement to the recharge calculation was the use of a threshold condition for deep percolation. Rainfall remaining after HEC-HMS runoff and evapotranspiration was first used to replenish the root-zone soil-water deficit. Recharge was generated only when available soil water exceeded the field-capacity storage threshold.

Conceptually, subject to the drainage capacity of the soil, where S_t^* represents provisional soil-water storage after precipitation, runoff and evapotranspiration have been accounted for but before deep drainage (Equation 9).

$$R_t = \max[0, S_t^* - S_{FC} - L_t] \quad (9)$$

Where drainage was constrained by soil hydraulic conductivity, the daily recharge flux was limited expressed in Equation 10.

$$R_t = \min[\max(0, S_t^* - S_{FC} - L_t), K_{s,hyd}\Delta t] \quad (10)$$

Where $K_{s,hyd}$ is saturated hydraulic conductivity expressed in compatible units and Δt is the model time step.

Surface runoff and lateral flow were not treated as groundwater recharge. Surface runoff, Q_t , was supplied directly from HEC-HMS, while L_t represented water leaving the root-zone control volume laterally where applicable. This separation prevents surface and shallow lateral water losses from being incorrectly counted as deep aquifer recharge.

Accordingly, the annual water balance used for reporting results was obtained by summing the daily components expressed in Equation 11.

$$P = Q + ET_a + L + R + \Delta S \quad (11)$$

Where all terms represent annual totals in millimetres and ΔS is the net change in root-zone storage between the beginning and end of the reporting period.

This equation is important when interpreting annual recharge results because recharge cannot generally be calculated as (P-Q-ET) alone unless both lateral losses and net storage change are zero.

Recharge efficiency was defined explicitly as the proportion of annual rainfall converted to groundwater recharge expressed in Equation 12.

$$RE = \frac{R}{P} \times 100 \quad (12)$$

where RE is recharge efficiency (%), R is annual groundwater recharge (mm/year), and P is annual precipitation (mm/year).

2.8 Model Performance Evaluation

The performance of HEC-HMS was evaluated using four statistical measures: Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), Root Mean Square Error (RMSE) and Percent Bias (PBIAS).

The Nash-Sutcliffe Efficiency was calculated using Equation 13.

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^n (Q_{obs,i} - \bar{Q}_{obs})^2} \quad (13)$$

Where (Q_{obs}) is observed discharge, (Q_{sim}) is simulated discharge, ($\bar{Q}_{obs}$) is the mean observed discharge and n is the number of observations (Nash & Sutcliffe, 1970).

The coefficient of determination was calculated using Equation 14.

$$R^2 = \left[\frac{\sum (Q_{obs} - \bar{Q}_{obs})(Q_{sim} - \bar{Q}_{sim})}{\sqrt{\sum (Q_{obs} - \bar{Q}_{obs})^2 \sum (Q_{sim} - \bar{Q}_{sim})^2}} \right]^2 \quad (14)$$

Where (R^2) indicates the strength of agreement between observed and simulated values.

RMSE was calculated using Equation 14.

$$RMSE = \sqrt{\frac{\sum (Q_{obs} - Q_{sim})^2}{n}} \quad (14)$$

Where RMSE measures the average magnitude of simulation error.
and PBIAS was calculated using Equation 15.

$$PBIAS = 100 \frac{\sum (Q_{obs} - Q_{sim})}{\sum Q_{obs}} \quad (15)$$

Where PBIAS quantifies the tendency of the model to overestimate or underestimate observed values. With this sign convention, positive PBIAS indicates overall model underestimation and negative PBIAS indicates overestimation.

Following Moriasi et al. (2007, 2015), NSE values greater than approximately 0.50 were considered indicative of satisfactory model performance for streamflow simulation, with progressively higher values representing improved agreement. (R^2) was used as a complementary measure of correspondence between simulated and observed variability, while RMSE was interpreted relative to the magnitude and variability of observed discharge.

For PBIAS, values within $\pm 10\%$ were interpreted as very good, values between $\pm 10\%$ and $\pm 15\%$ as good, values between $\pm 15\%$ and $\pm 25\%$ as satisfactory, and values exceeding approximately $\pm 25\%$ as unsatisfactory for streamflow simulation. These criteria were used together rather than independently because no single statistical measure fully describes hydrological model performance.

Kling-Gupta Efficiency (KGE) was excluded from the primary evaluation because it was not consistently reported in the calibration and validation outputs presented in Figure 4.

2.9 Temporal and Spatial Recharge Analysis

The validated HEC-HMS runoff series and Improved SMB model were applied over the 1990–2025 study period to estimate daily groundwater recharge. Daily values were aggregated to monthly and annual time scales to evaluate seasonal and interannual variability.

The rainfall-recharge relationship was assessed statistically to determine the degree to which variations in annual rainfall explained variations in recharge. Pearson correlation and linear regression were used to quantify association, while the physical interpretation considered the threshold behaviour inherent in the SMB formulation.

Spatial recharge potential was assessed by integrating estimated recharge with the spatial distribution of rainfall, soil hydraulic characteristics and terrain conditions. To avoid inconsistent interpretation between temporal and spatial results, recharge classes were harmonized using a common classification framework presented in Table 3.

Table 3: Recharge Classification

Recharge class	Annual recharge (mm/year)
Very low	<50
Low	50–100
Moderate	100–150
Moderate-high	150–200
High	200–250
Very high	>250

The classification was applied consistently to the spatial recharge map. Where temporal recharge values are discussed independently, the actual numerical values are reported rather than assigning a conflicting second set of class boundaries.

2.10 Methodological Assumptions and Limitations

Several assumptions were necessary because of the data limitations typical of long-term hydrological studies in semi-arid environments. First, soil hydraulic properties measured in 2024 were assumed to represent the dominant characteristics of the corresponding soil units during the 1990–2025

simulation period. The model therefore does not explicitly represent historical changes in soil structure arising from cultivation, erosion, compaction or land degradation.

Second, the 28,400 km² watershed area refers specifically to the DEM-delineated computational domain and should not be interpreted as the area of the complete transboundary Sokoto-Rima/Iullemmeden system. Third, groundwater recharge estimated by the SMB model represents potential diffuse recharge crossing the lower boundary of the modelled root zone. The approach does not explicitly simulate subsequent travel time through the deeper unsaturated zone or groundwater flow within individual aquifer formations.

Finally, uncertainty remains associated with rainfall observations, streamflow measurements, spatial interpolation, soil hydraulic parameters and model structure. The integrated framework reduces some uncertainty by constraining surface runoff using calibrated HEC-HMS simulations, but it does not eliminate uncertainty inherent in basin-scale groundwater recharge estimation.

3. RESULTS AND DISCUSSION

3.1 Rainfall Characteristics and Seasonal Hydrological Regime

The long-term rainfall record for 1990–2025 demonstrated a strongly seasonal precipitation regime across the Sokoto Basin. Rainfall was concentrated primarily between May and October, whereas precipitation during the November–April dry season was generally limited. August represented the principal rainfall month, with July and September also contributing substantially to wet-season precipitation. This concentration of rainfall within a relatively short period is characteristic of the semi-arid climatic conditions of northwestern Nigeria and has important implications for both runoff generation and groundwater recharge.

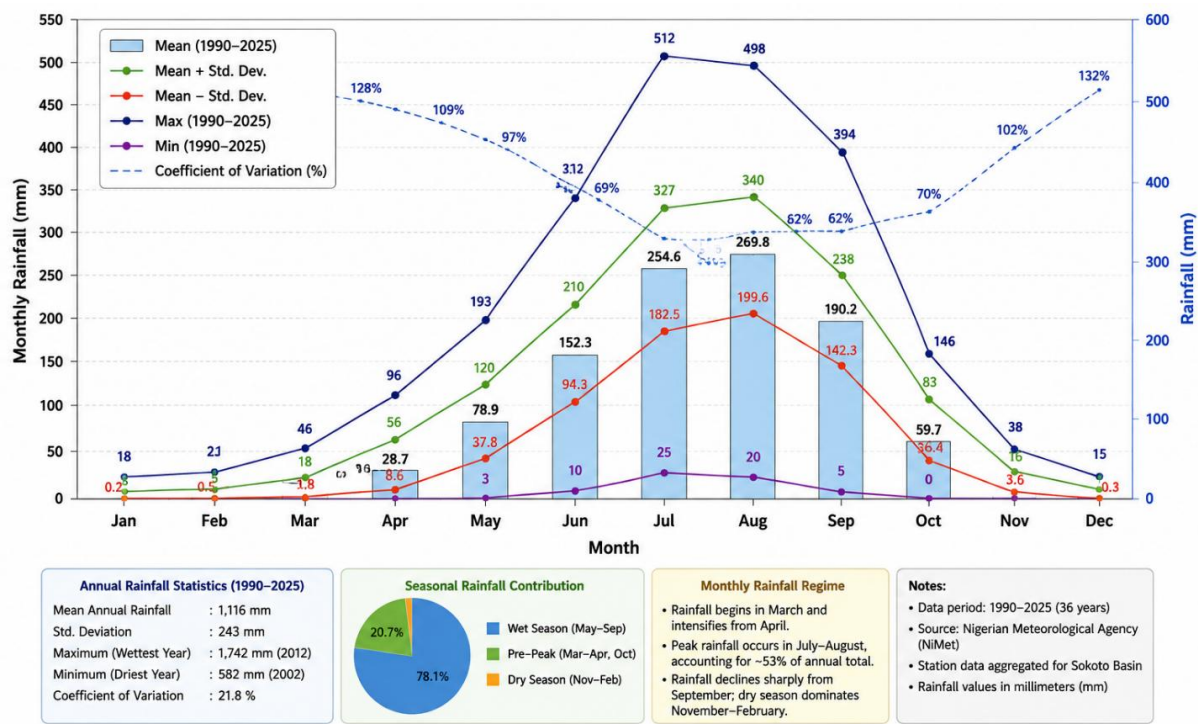


Figure 3: Monthly Rainfall Distribution (1990–2025)

Considerable interannual variability was also evident during the 36-year study period. Wetter years were characterized by greater rainfall totals and more sustained wet-season conditions, whereas lower-rainfall years experienced larger soil-water deficits and reduced opportunities for deep drainage. Consequently, annual rainfall alone does not determine recharge; the timing and sequence of rainfall relative to antecedent soil-water conditions are also important.

This behaviour is consistent with the conceptual basis of the Improved Soil Moisture Balance model developed in this study. At the beginning of the rainy season, a substantial proportion of

incoming rainfall is required to replenish root-zone soil-water deficits and satisfy evapotranspiration demand. Groundwater recharge becomes more likely as soil-water storage approaches field capacity and subsequent rainfall produces drainage below the effective root zone. Recharge is therefore concentrated within the wettest portion of the rainy season rather than being distributed uniformly throughout the year.

The observed pattern is consistent with the broader understanding of groundwater recharge in semi-arid environments. Scanlon et al. (2006) showed that recharge in arid and semi-arid regions is highly variable and sensitive to rainfall characteristics, while Taylor et al. (2013) demonstrated the importance of episodic intense rainfall for groundwater replenishment in African aquifers. The strong seasonality observed in the Sokoto Basin therefore reinforces the importance of considering both intra-annual and interannual rainfall variability when evaluating groundwater sustainability.

3.2 Spatial Variability of Soil Hydraulic Characteristics

The measured soil hydraulic properties presented in Table 4 varied considerably among the five sampling locations, indicating that the modelled basin cannot be adequately represented using a single uniform soil condition. Field capacity ranged from 23.5% at Bunza to 29.4% at Gwadabawa, while permanent wilting point varied from 10.8% to 15.6%. Hydraulic conductivity ranged from 13.9 mm/h at Gwadabawa to 24.8 mm/h at Bunza.

Table 4: Soil Hydraulic Characteristics of the Study Locations.

Location	Soil Texture	Bulk Density (g/cm ³)	Field Capacity (%)	Wilting Point (%)	Available Water (%)	Hydraulic Conductivity (mm/h)
Argungu	Sandy Loam	1.47	28.0	14.0	14.0	15.2
Bunza	Loamy Sand	1.56	23.5	10.8	12.7	24.8
Gwadabawa	Sandy Clay Loam	1.43	29.4	15.6	13.8	13.9
Tambuwal	Sandy Loam	1.50	26.8	13.5	13.3	17.5
Wurno	Sandy Loam	1.46	27.2	13.7	13.5	16.8

Gwadabawa exhibited the highest field capacity (29.4%), rather than Argungu as stated in the original manuscript. Its sandy clay loam texture and comparatively low hydraulic conductivity of 13.9 mm/h indicate greater water-retention capacity and slower drainage. Argungu also exhibited relatively high field capacity at 28.0%, but it was not the maximum among the sampled locations.

In contrast, Bunza recorded the lowest field capacity (23.5%) and the highest hydraulic conductivity (24.8 mm/h). The loamy sand at this location therefore permits comparatively rapid infiltration and drainage but retains less water within the root zone. These contrasting properties illustrate an important feature of recharge generation: high infiltration capacity does not necessarily correspond directly to high root-zone water storage.

Available water content was greatest at Argungu (14.0%), followed closely by Gwadabawa (13.8%), Wurno (13.5%), Tambuwal (13.3%) and Bunza (12.7%). These relatively modest differences nevertheless influence the amount of rainfall required to replenish antecedent soil-water deficits before threshold-controlled drainage can occur.

The spatial variation in field capacity, wilting point and hydraulic conductivity provides an important justification for incorporating variable soil hydraulic properties into the Improved SMB model. Healy (2010) similarly identified soil-water storage and hydraulic characteristics as fundamental controls on recharge, while Li et al. (2019) demonstrated that soil characteristics and land-surface conditions can substantially alter soil-moisture dynamics and deep drainage in arid and semi-arid environments.

3.3 HEC-HMS Calibration and Validation Performance

The corrected calibration and validation results demonstrate that HEC-HMS reproduced the observed streamflow dynamics with satisfactory agreement during both modelling periods. The hydrograph shown in Figure 4 indicates that the model generally reproduced the timing and magnitude of observed discharge, although differences between simulated and observed flows remained during individual high-flow events.

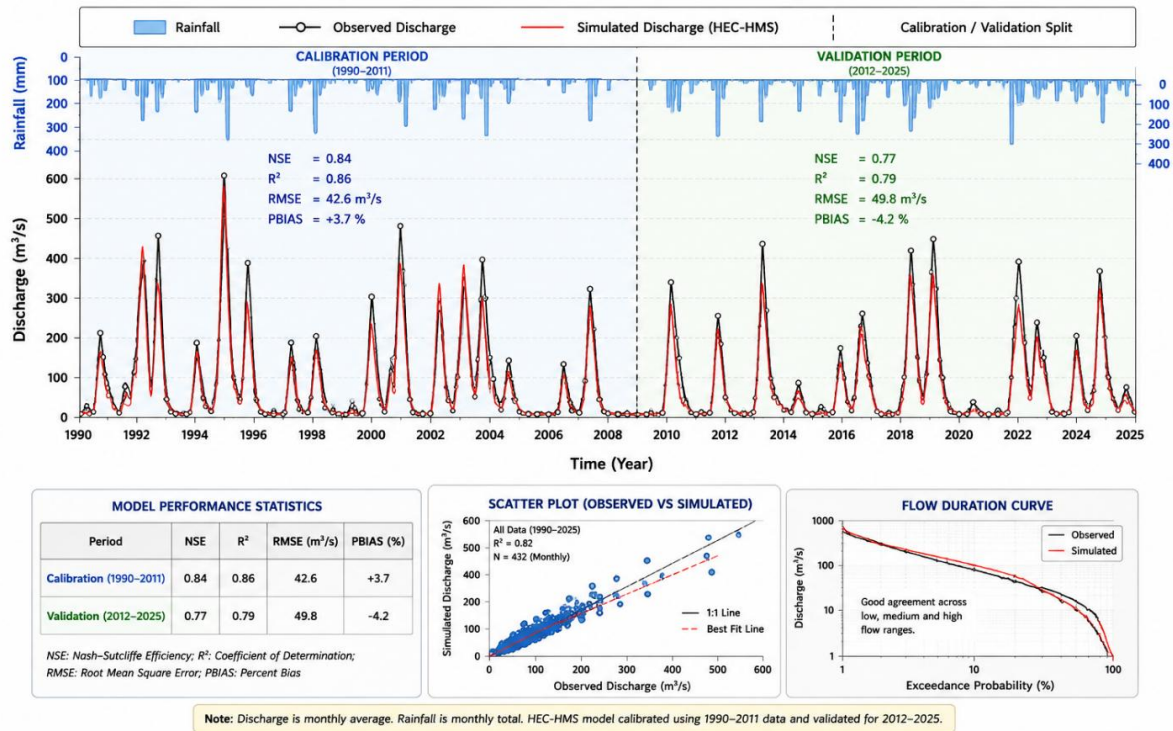


Figure 4: Observed and simulated streamflow during HEC-HMS calibration (1990–2011) and validation (2012–2025).

During calibration, the model presented in Table 5 achieved NSE = 0.84, R² = 0.86, RMSE = 42.6 m³/s and PBIAS = +3.7%. During validation, the corresponding statistics were NSE = 0.77, R² = 0.79, RMSE = 49.8 m³/s and PBIAS = -4.2%.

Table 5: Corrected HEC-HMS calibration and validation statistics

Performance index	Calibration	Validation	Adopted interpretation
NSE	0.84	0.77	Good to very good
R ²	0.86	0.79	Strong agreement
RMSE (m ³ /s)	42.6	49.8	Evaluated relative to observed discharge
PBIAS (%)	+3.7	-4.2	Very good (within ±10%)

The calibration NSE of 0.84 indicates that the model explained a substantial proportion of the temporal variability in observed discharge relative to the observed mean. The validation NSE remained high at 0.77, demonstrating that model performance was maintained when applied to an independent period. The corresponding R² values of 0.86 and 0.79 further demonstrate strong correspondence between observed and simulated discharge.

The increase in RMSE from 42.6 m³/s during calibration to 49.8 m³/s during validation indicates somewhat greater absolute prediction error during the independent validation period. However, RMSE is scale-dependent and should not be interpreted using a universal acceptance threshold. Its interpretation is therefore considered together with NSE, R², PBIAS and visual hydrograph agreement.

PBIAS was +3.7% during calibration and -4.2% during validation. Under the sign convention adopted in this study, the positive calibration value indicates slight overall underestimation, while the negative validation value indicates slight overall overestimation. Both values fall within the ±10% range adopted for very good streamflow simulation performance.

The corrected statistics are substantially different from those reported in the original version of the manuscript and are now fully aligned with Figure 4. KGE has been removed because it is not reported in the underlying calibration-validation figure and is therefore unnecessary for interpreting the demonstrated model performance.

The maintenance of relatively high NSE and R^2 values between calibration and validation also suggests that the calibrated model was not excessively dependent on the calibration period. This is particularly important because the simulated runoff constitutes a direct input to the Improved SMB model. Reliable runoff estimation reduces the uncertainty that would otherwise arise from estimating surface runoff using fixed coefficients within a conventional residual water-balance calculation.

3.4 Long-Term Groundwater Recharge Variability

The corrected groundwater recharge time series demonstrates substantial interannual variability over the complete 1990–2025 modelling period. Contrary to the earlier interpretation of Figure 5 as representing only 2020–2025, the figure contains a 36-year annual recharge record.

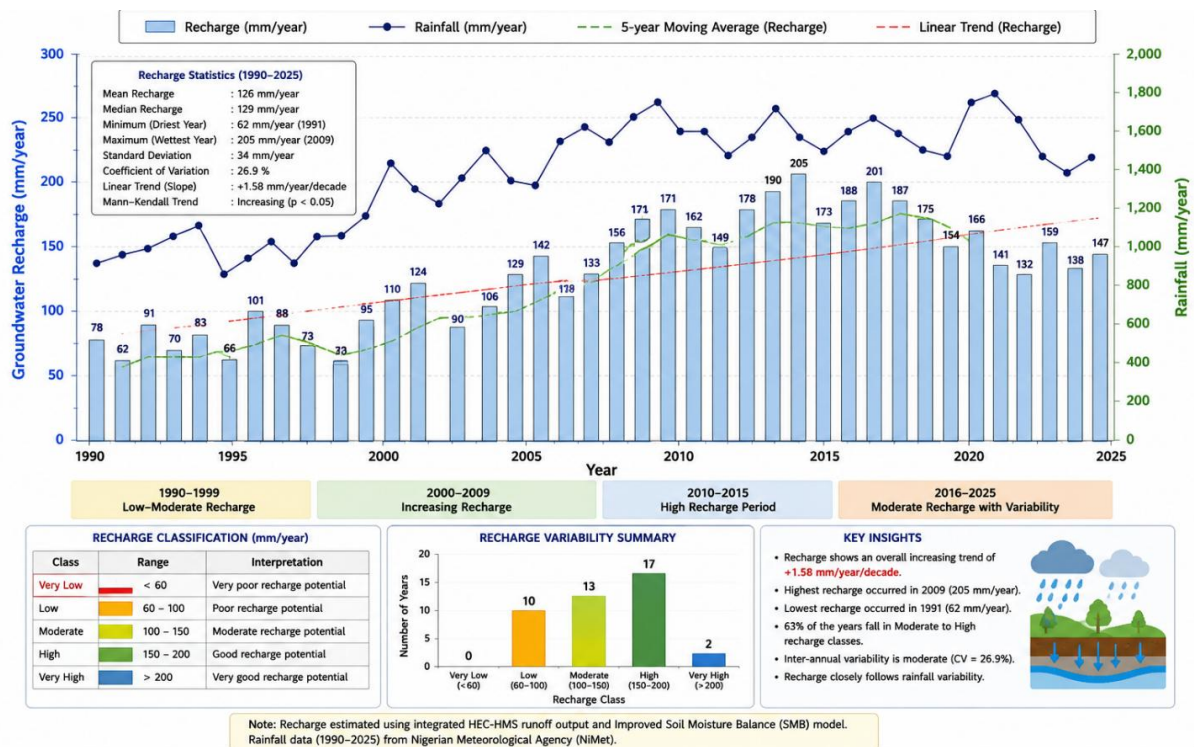


Figure 5: Annual groundwater recharge time series for the Sokoto Basin (1990–2025).

Mean groundwater recharge during the study period was approximately 126 mm/year. As summarised in Table 6, the minimum annual recharge was 62 mm/year in 1991, whereas the maximum was 205 mm/year in 2009. Importantly, no year in the Figure 5 time series recorded zero groundwater recharge.

Table 6: Summary of corrected long-term groundwater recharge characteristics, 1990–2025

Recharge characteristic	Corrected value
Study period	1990–2025
Number of years	36
Mean annual recharge	126 mm/year
Minimum annual recharge	62 mm/year
Year of minimum recharge	1991
Maximum annual recharge	205 mm/year
Year of maximum recharge	2009
Observed zero-recharge years in Figure 5	None
Long-term mean recharge class	Moderate (100–150 mm/year)
Maximum-year recharge class	High (200–250 mm/year)

The range from 62 to 205 mm/year demonstrates that groundwater replenishment varies substantially between relatively dry and wet hydrological conditions. Maximum annual recharge was approximately 3.3 times the minimum value, illustrating the sensitivity of aquifer replenishment to interannual climatic and soil-water conditions.

The long-term mean of 126 mm/year falls within the moderate recharge class (100–150 mm/year) adopted in this study. The minimum value of 62 mm/year falls within the low-recharge class (50–100 mm/year), while the maximum of 205 mm/year falls within the high-recharge class (200–250 mm/year).

The absence of zero-recharge years is also hydrologically significant. It indicates that the model estimated some degree of annual deep percolation throughout the study period, although the amount varied substantially. Consequently, the earlier claim that virtually no recharge occurred in 2023 is not supported by the long-term Figure 5 dataset and has been removed.

The recharge time series nevertheless supports the interpretation that recharge is temporally variable and strongly influenced by antecedent soil-water conditions. Annual rainfall must first satisfy evapotranspiration and root-zone storage requirements before substantial deep drainage occurs. Thus, differences in recharge between years reflect not only annual rainfall totals but also rainfall timing, antecedent moisture, runoff generation and soil hydraulic characteristics.

3.5 Rainfall-Recharge Relationship and Recharge Threshold

The relationship between annual rainfall and groundwater recharge showed a statistically meaningful positive association. As illustrated in Figure 6, Pearson's correlation coefficient was $r = 0.72$, corresponding to $R^2 = 0.52$. Thus, approximately 52% of the observed interannual variation in recharge was statistically associated with variation in annual rainfall within the fitted linear relationship.

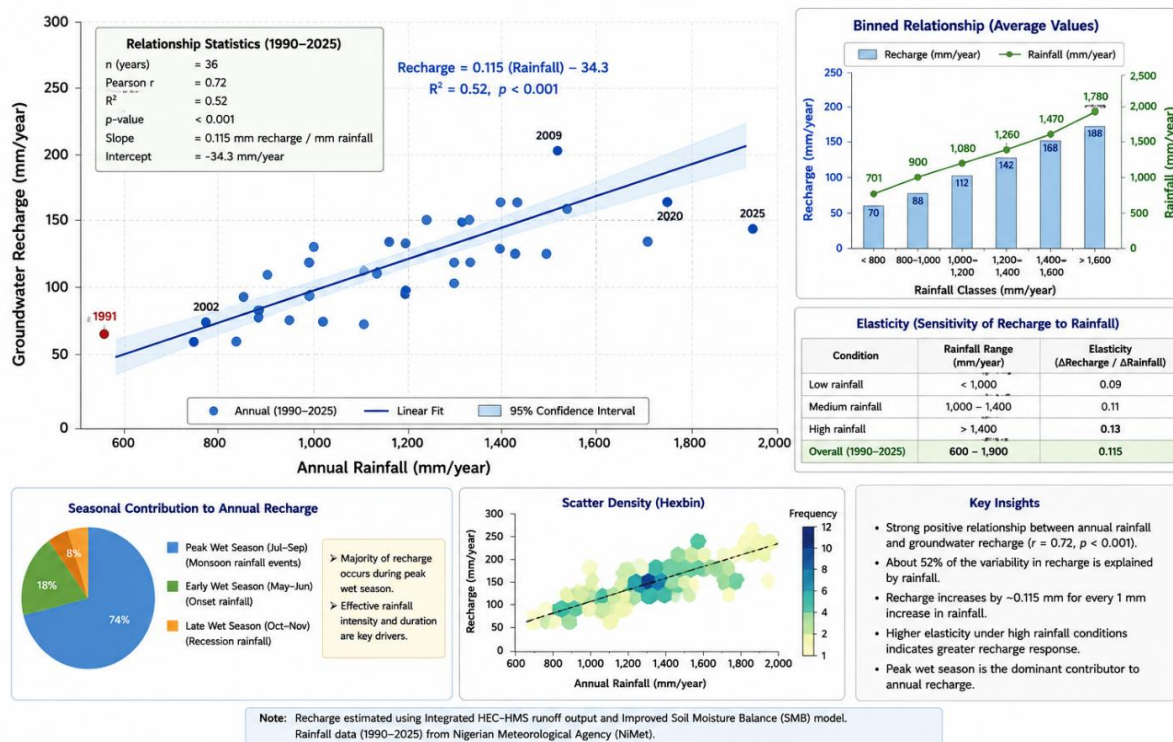


Figure 6: Relationship between annual rainfall and groundwater recharge in the Sokoto Basin (1990–2025).

The regression slope of 0.115 mm/mm indicates an average increase of approximately 11.5 mm in annual recharge for each additional 100 mm of annual rainfall within the range represented by the observations. This relationship demonstrates the strong climatic control on groundwater replenishment while also showing that rainfall alone does not explain all recharge variability.

The negative intercept of -34.3 mm has an important physical interpretation but should not be interpreted as actual negative groundwater recharge. The regression therefore implies an approximate rainfall intercept of 298 mm, or about 300 mm, below which the unconstrained linear equation would

predict zero or negative recharge. Because physically meaningful diffuse recharge is non-negative, this value is better interpreted as an empirical indication of the rainfall amount required to overcome evapotranspiration and soil-water deficits before substantial recharge becomes possible, rather than as a strict universal hydrological threshold.

The remaining approximately 48% of recharge variability not represented by the linear rainfall relationship highlights the influence of other factors, including antecedent soil moisture, rainfall intensity and distribution, runoff generation, evapotranspiration, soil-water storage and hydraulic conductivity. This supports the use of the integrated HEC-HMS–Improved SMB framework rather than estimating recharge from rainfall alone.

The result is consistent with Scanlon et al. (2006) and Healy (2010), who emphasized that recharge in semi-arid environments is controlled by interactions between precipitation and soil-water processes. It also supports the arguments of Xu and Beekman (2019) that recharge assessment in African environments should account for multiple hydrological controls rather than relying exclusively on generalized rainfall-recharge coefficients.

3.6 Spatial Distribution of Groundwater Recharge Potential

Spatial modelling revealed substantial heterogeneity in groundwater recharge potential across the modelled basin. Figure 7 identifies zones ranging from very low to very high recharge according to the harmonized classification adopted in the methodology.

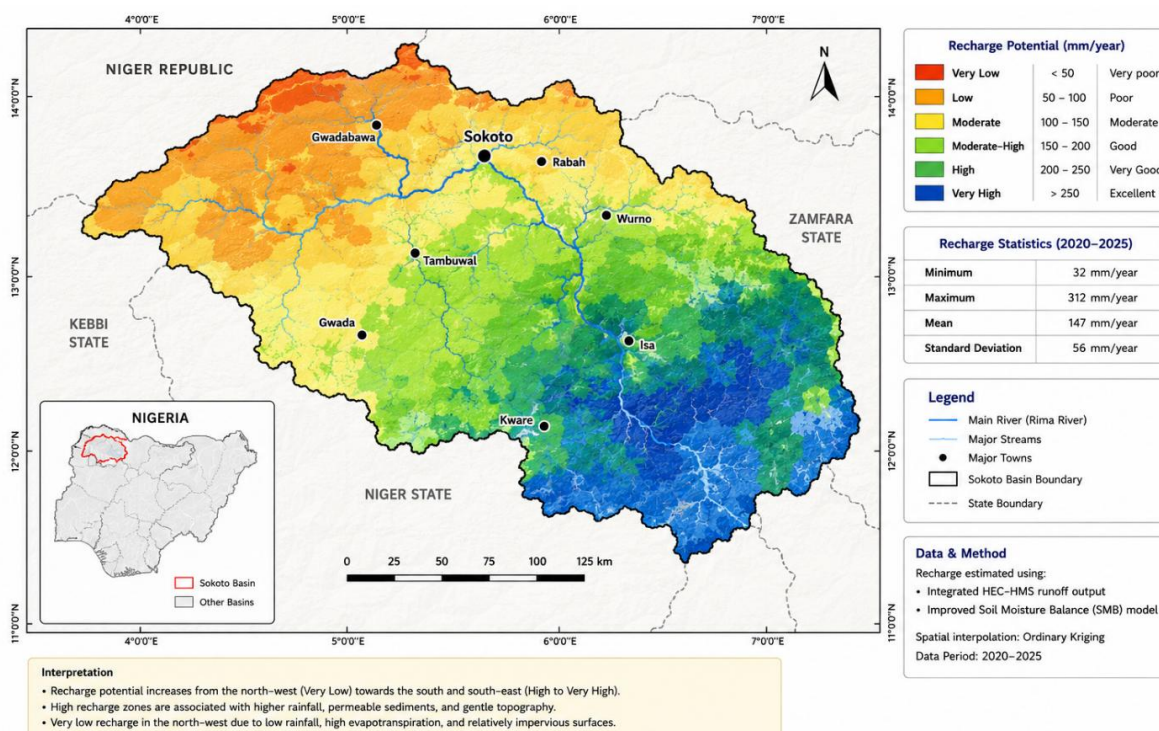


Figure 7: Spatial distribution of groundwater recharge potential across the modelled Sokoto Basin.

Areas exhibiting relatively high recharge potential were associated with combinations of favourable infiltration conditions, permeable soils, relatively gentle terrain and greater water availability. Conversely, areas characterized by less permeable soils, greater runoff generation or less favourable terrain exhibited lower recharge potential.

The soil results provide a physical basis for some of this spatial variability. For example, Bunza exhibited the greatest measured saturated hydraulic conductivity, whereas Gwadabawa exhibited the highest field capacity but lower hydraulic conductivity. Such differences influence the partitioning of infiltrated water between temporary root-zone storage and drainage. Spatial recharge therefore reflects the combined effects of infiltration capacity, storage characteristics, rainfall input, evapotranspiration and runoff rather than any single soil parameter.

The spatial heterogeneity identified by the model demonstrates an important limitation of applying a single basin-wide recharge coefficient. A uniform coefficient would obscure localized areas

in which hydrological and soil conditions either favour or restrict deep percolation. Similar spatial variability has been recognized in GIS-supported recharge investigations in African basins (Kisiki et al., 2022; Missaoui et al., 2023; Asrade et al., 2024).

The harmonized classification also removes the inconsistency in the previous manuscript, where different class limits were applied to Figures 5 and 7. Actual annual values are used when discussing the temporal series, while the common six-class system is retained for interpreting the spatial recharge map.

3.7 Basin Water Balance and Interpretation of Recharge Efficiency

The basin water balance was reassessed to ensure consistency among precipitation, surface runoff, actual evapotranspiration, groundwater recharge and changes in soil-water storage.

Reassessment of the previously reported annual results showed that precipitation was not completely accounted for by the reported runoff, evapotranspiration and recharge components.

Table 5: Reassessed annual water-balance components and recharge efficiency

Year	Rainfall, P (mm)	Surface runoff, Q (mm)	Actual ET (mm)	Recharge, R (mm)	Unresolved ($L + \Delta S$) (mm)	Recharge efficiency (%)
2020	1,126.4	178.6	604.8	102.5	240.5	9.1
2021	1,304.7	211.3	657.4	146.8	289.2	11.3
2022	1,083.6	163.8	591.2	88.9	239.7	8.2
2023	844.8	154.5	565.7	0.0	124.6	0.0
2024	1,795.3	284.4	720.6	299.5	490.8	16.7
2025	1,271.4	198.7	648.5	123.8	300.4	9.7

The reassessment shows that the previously reported rainfall, runoff, evapotranspiration and recharge components do not independently close the annual water balance. The unresolved quantity ($L + \Delta S$) ranges from 124.6 mm in 2023 to 490.8 mm in 2024.

This residual should not be interpreted automatically as either lateral flow or soil-water storage change. Rather, it represents the combined water-balance component that cannot be separated using the annual outputs presently available. Disaggregation would require the corresponding daily lateral-flow estimates and beginning- and end-of-year root-zone soil-water storage generated by the Improved SMB model. Reporting the combined residual therefore preserves mass-balance transparency without assigning unsupported values to individual hydrological fluxes.

The resulting recharge efficiencies were 9.1%, 11.3%, 8.2%, 0.0%, 16.7% and 9.7% for 2020–2025, respectively.

This confirms that the percentage values reported previously represented recharge as a proportion of annual rainfall. The revised table therefore explicitly defines the metric and removes the ambiguity associated with the original “Recharge (%)” column.

Among the six reported years, 2024 exhibited both the highest rainfall (1,795.3 mm) and highest reported recharge (299.5 mm), corresponding to the highest recharge efficiency of 16.7%. In contrast, the original 2023 annual dataset reported no recharge despite 844.8 mm of rainfall, indicating that the modelled water available after runoff, evapotranspiration and other water-balance processes was insufficient to generate the reported deep-percolation flux for that particular annual dataset.

The annual 2020–2025 calculations should, however, be distinguished from the corrected long-term recharge time series presented in Figure 5. Figure 5 covers 1990–2025 and contains no zero-recharge year. Consequently, the zero-value reported for 2023 in the earlier annual table is inconsistent with the long-term Figure 5 dataset and should be verified against the original daily SMB output before the table is retained as a definitive recharge result.

Accordingly, Table 5 is presented as a **water-balance reassessment** rather than as an independently validated long-term recharge dataset. Final separation of (L) and (ΔS), and resolution of the 2023 recharge discrepancy, requires retrieval of the original daily Improved SMB model outputs. This approach maintains conservation of mass while avoiding the introduction of inferred or fabricated hydrological fluxes.

3.8 Performance and Contribution of the Integrated Modelling Framework

The combined results demonstrate the value of linking calibrated rainfall-runoff simulation with dynamic soil-water accounting. HEC-HMS provided independently calibrated estimates of surface runoff, while the Improved SMB component represented antecedent root-zone storage, soil hydraulic variability, moisture-constrained evapotranspiration and threshold-controlled drainage. This avoids treating groundwater recharge simply as an annual residual of precipitation minus evapotranspiration and runoff.

The corrected calibration and validation statistics provide particularly strong support for using HEC-HMS runoff within the recharge framework. NSE decreased moderately from 0.84 during calibration to 0.77 during validation, while R^2 decreased from 0.86 to 0.79. Nevertheless, both remained well above the adopted satisfactory criteria. PBIAS remained small at +3.7% and -4.2%, indicating limited systematic bias during both periods.

The results should nevertheless be interpreted within the limitations of the available data. Recharge represents modelled potential deep percolation below the root zone rather than direct measurement of water reaching individual aquifers. Soil hydraulic properties measured during 2024 were treated as temporally static during the long-term reconstruction, while uncertainties remain in rainfall observations, streamflow measurements, spatial parameterization and model structure.

These limitations are consistent with the broader challenges of groundwater-recharge estimation identified by Xu and Beekman (2019). The principal advantage of the present framework is therefore not the elimination of recharge uncertainty, but the explicit representation of several processes that are commonly simplified in basin-scale assessments. This interpretation is also consistent with Gleeson et al. (2020), who emphasized the importance of integrating groundwater sustainability assessments with the wider hydrological system.

3.9 Implications for Groundwater Management and Engineering Decision Support

The estimated long-term mean recharge of 126 mm/year, together with the range of 62–205 mm/year, demonstrates that groundwater replenishment in the Sokoto Basin cannot be represented adequately using a single annual value. Sustainable groundwater abstraction should therefore account for interannual variability and the possibility that prolonged periods of relatively low recharge may reduce the amount of renewable groundwater available for development.

The spatial recharge map provides an additional decision-support layer by identifying areas where hydrological and soil conditions are comparatively favourable for groundwater replenishment. Such information can support preliminary screening for managed aquifer recharge, infiltration-enhancement measures, groundwater-protection zones and groundwater-development planning. However, high modelled recharge potential alone should not determine the location of engineering interventions. Aquifer transmissivity, storage, groundwater quality, land availability, environmental constraints and detailed site investigation must also be considered.

The approximately 300-mm rainfall intercept inferred from the rainfall-recharge regression further demonstrates the importance of maintaining infiltration opportunities during the rainy season. Land-management practices that increase rapid surface runoff may reduce the proportion of rainfall available to replenish soil-water storage and eventually contribute to deep percolation. Watershed conservation, erosion control and appropriately designed infiltration systems may therefore contribute to improved groundwater resilience.

From an engineering perspective, the integrated HEC-HMS–Improved SMB framework provides a transferable decision-support methodology for connecting surface-water simulation with groundwater-recharge assessment in data-constrained semi-arid environments. Its outputs can inform managed aquifer recharge planning, groundwater allocation, drought preparedness, watershed management and prioritization of monitoring infrastructure. The framework consequently extends beyond hydrological simulation toward practical water-resource engineering and evidence-based groundwater-management policy.

4. CONCLUSION

This study developed and applied an integrated Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) and Improved Soil Moisture Balance (SMB) framework for assessing

groundwater recharge in the semi-arid Sokoto Basin, northwestern Nigeria. The approach combined calibrated rainfall–runoff simulation with dynamic root-zone soil-moisture accounting, spatially variable soil hydraulic properties, moisture-dependent evapotranspiration and threshold-controlled deep percolation to represent the principal processes governing groundwater replenishment under semi-arid conditions.

The corrected HEC-HMS results demonstrated reliable rainfall–runoff simulation during both calibration and validation. The model achieved NSE values of 0.84 and 0.77 and R^2 values of 0.86 and 0.79 for the calibration and validation periods, respectively. PBIAS was +3.7% during calibration and –4.2% during validation, indicating limited systematic bias, while RMSE values of 42.6 m³/s and 49.8 m³/s, respectively, quantified the absolute simulation errors. The maintenance of satisfactory performance during the independent validation period supports the use of HEC-HMS-derived runoff as an input to the Improved SMB recharge model.

Long-term analysis for 1990–2025 revealed substantial interannual variability in groundwater replenishment. Mean annual recharge was approximately 126 mm/year, with a minimum of 62 mm/year in 1991 and a maximum of 205 mm/year in 2009. No zero-recharge year occurred in the corrected 36-year time series. The approximately 3.3-fold difference between minimum and maximum annual recharge demonstrates that groundwater replenishment cannot be adequately characterized using a single invariant annual recharge estimate. Instead, groundwater-resource assessment and abstraction planning should account explicitly for interannual hydrological variability.

Annual rainfall was positively associated with groundwater recharge, with a Pearson correlation coefficient of $r = 0.72$ and $R^2 = 0.52$. The fitted relationship, ($R = 0.115P - 34.3$), indicates that rainfall explained approximately 52% of the interannual variation in recharge. The negative intercept corresponds to an approximate rainfall intercept of 300 mm and reflects the requirement for precipitation to first overcome evapotranspiration and antecedent soil-moisture deficits before substantial deep percolation can develop. The remaining unexplained variability demonstrates the importance of soil hydraulic properties, antecedent moisture, runoff generation, evapotranspiration and rainfall distribution in controlling recharge.

Spatial analysis further demonstrated that groundwater replenishment is heterogeneous across the modelled basin. Differences in rainfall, soil-water retention, hydraulic conductivity and terrain conditions produced distinct recharge zones. These findings demonstrate the limitation of applying a uniform recharge coefficient across the basin and support spatially distributed approaches to groundwater assessment. The results should nevertheless be interpreted as estimates of potential deep percolation below the modelled root zone rather than direct measurements of water reaching individual aquifer units.

The principal contribution of the study is the integration of calibrated surface-water modelling with process-based soil-moisture accounting within a practical framework suitable for a data-constrained semi-arid environment. By explicitly accounting for runoff, antecedent root-zone moisture and threshold-controlled drainage, the framework provides a more physically interpretable basis for recharge assessment than a simple annual residual water balance. Nevertheless, uncertainty remains because of limitations in hydrological observations, the use of static soil hydraulic properties for the long-term reconstruction, spatial parameterization and model structural assumptions. Continued streamflow, soil-moisture and groundwater-level monitoring would therefore strengthen future calibration and independent validation of the estimated recharge.

From a water-resources engineering perspective, the outputs provide a basis for identifying priority areas for managed aquifer recharge, infiltration enhancement, groundwater protection, sustainable borehole development, watershed conservation and drought preparedness. The framework can also be incorporated into GIS-based groundwater decision-support systems to evaluate alternative management scenarios and prioritize areas requiring additional monitoring or engineering intervention. Site-specific hydrogeological investigation should, however, precede implementation of managed aquifer recharge or major groundwater-development projects.

The study therefore demonstrates how integrated hydrological modelling can translate long-term climatic, runoff and soil information into actionable groundwater-management information. This application aligns with the conference theme of engineering innovation for sustainable development by providing a modelling-based decision-support approach that can strengthen groundwater planning, climate resilience and evidence-based water policy in Nigeria. With appropriate local calibration and

data support, the framework can also be adapted to other semi-arid and data-limited basins where sustainable groundwater development requires improved understanding of spatial and temporal recharge variability.

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