
ESTIMATING GROUNDWATER RECHARGE IN THE BIDA BASIN USING INTEGRATED SOIL MOISTURE BALANCE AND HEC-HMS MODELLING: A CASE STUDY OF THE NEW BUSSA SUB-BASIN

Salihu Mohammed^{1,*}

¹*Federal University of Technology Minna*

Email: saleehu42@gmail.com*

*Corresponding author: Salihu Mohammed

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ABSTRACT

Groundwater is the principal source of domestic and agricultural water supply across tropical Africa, yet its sustainable management is constrained by a poor understanding of recharge processes. This study evaluates groundwater recharge dynamics in the Bida Basin, north-central Nigeria, using the New Bussa sub-basin (Borgu Local Government Area) as a representative catchment. Twenty-five years (2000–2025) of meteorological data were integrated with laboratory-derived soil properties, a Python-based Soil Moisture Balance (SMB) model, and the Hydrologic Engineering Center–Hydrologic Modelling System (HEC-HMS). In the absence of an independently gauged streamflow station, HEC-HMS parameter calibration (Curve Number 40–85, lag time 100–323 min, imperviousness 10–25%) was executed against SMB-derived synthetic run-off to evaluate inter-model consistency rather than field-validated predictive accuracy. The best-fit inter-model agreement yielded a Nash–Sutcliffe Efficiency (NSE) of 0.52 and R^2 of 0.797 at CN = 40, T_{Lag} 100min and imperviousness 10%. Over the 2020–2024 simulation period, mean annual rainfall was 1,199.32 mm, of which 273.96 mm (22.8%) was converted to run-off, while simulated groundwater recharge averaged 31.96 mm/yr (2.7%). Groundwater recharge was zero during 2021–2024 (0.00 mm/yr) and occurred exclusively during the exceptionally wet year of 2020 (159.81 mm). Sensitivity analysis indicates this threshold-controlled recharge response is highly governed by the specified root-zone depth ($Z_r=0.9$ m) and depletion factor ($p=0.2–0.7$). Soil was classified as sandy loam with moderate bulk density (1.46–1.61 g/cm³) and available water capacity (10.2–12.2%). These findings depict a runoff-dominated hydrological regime where recharge is episodic, serving as a baseline hypothesis for comparable sub-humid tropical savannah catchments across the Middle Niger region.

Keywords: Groundwater Recharge; Soil Moisture Balance Model; HEC-HMS; Bida Basin; Nash–Sutcliffe Efficiency; New Bussa

1. INTRODUCTION

Groundwater recharge is the process by which water moves downward from the Earth's surface to the water table, replenishing the aquifer. This process is a critical component of sustainable water resources management (Shaikh and Birajdar, 2024). Nearly half of the world's population relies on groundwater for domestic and agricultural purposes (Scanlon et al., 2023), while across sub-Saharan Africa, it serves as the primary supply for rural and urban livelihoods (Ogunbode et al., 2024). Recharge rates are governed by interacting climatic, pedological, land-surface, and hydrogeological factors (Müller, 2023).

Quantifying recharge remains challenging in data-scarce tropical environments. While techniques such as the Water Table Fluctuation (WTF) method calculate recharge based on water-table rises and specific yield (Sy), their application is severely constrained by short-term temporal validity, high sensitivity to Sy uncertainties, and a total reliance on dense piezometric monitoring networks (Healy & Cook, 2002; Rushton et al., 2006). In un-gauged or sparsely monitored catchments where continuous groundwater-level observations are unavailable, physical numerical models offer a viable alternative.

In Nigeria's Bida Basin, rising agricultural and industrial abstractions have intensified pressure on subsurface reservoirs (Olaleye et al., 2025; Cuthbert et al., 2023). To address these observational data gaps, this study couples a Python-based Soil Moisture Balance (SMB) model

with HEC-HMS to simulate continuous root-zone moisture flux and catchment run-off in the New Bussa sub-basin.

2. METHODOLOGY

2.1 Study Area

New Bussa is located at about 9.88° N, 4.51° E in the Guinea savanna zone of Borgu LGA, Niger State, at an elevation of 180–200 m. The town was resettled due to the creation of Kainji Lake from the River Niger. It lies within the Niger River Basin where the Niger and Kaduna rivers meet, featuring rolling land and various types of land cover. The climate is tropical savanna, with a wet season from May to September and a dry season from October to April. Figures 2.1 and 2.2 show the Bida Basin and Study Area (New Bussa) in Borgu LGA, located within the Bida Basin.

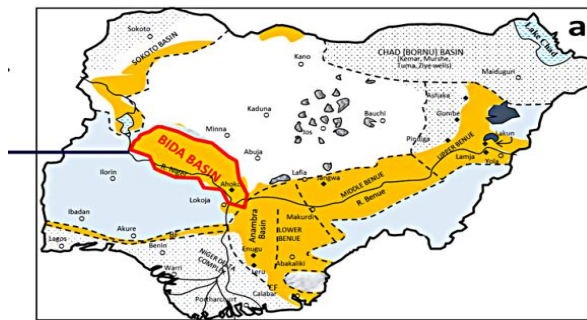


Figure 2.1: Map of Nigeria Showing the Bida Basin in Red.

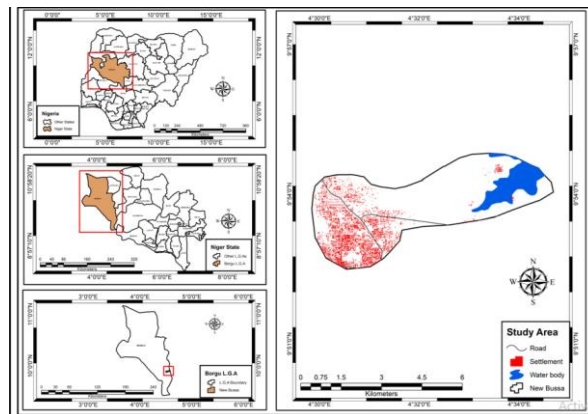


Figure 2.2: Map of Nigeria Showing the Study Area (New Bussa).

2.2 Data Acquisition

Daily rainfall and temperature data (maximum and minimum) from 2000 to 2025 were collected from the Nigerian Meteorological Agency. Reference evapotranspiration was calculated using the Hargreaves method. Soil samples from the study area were analysed to determine soil properties: bulk density, Field capacity (FC), and wilting point (WP) in the laboratory. The SMB model was run continuously from 2000 to 2025, but the final analysis was focused on 2020 to 2024 for calibration relevance.

2.3 Soil Moisture Balance Model

A Python implementation of the SMBM computed the daily water balance of the root zone (maximum rooting depth $Z_r = 0.9$ m). Total and readily available water were computed as $TAW = (FC - WP) \times 1000 \times Z_r$ and $RAW = TAW \times \rho$, where ρ is a depletion factor of 0.2–0.7 (Allen et al., 1998). Daily soil-moisture deficit (SMD) was updated as $SMD' = SMD_{prev} + AE - AWE + NSS$, where AE is actual evapotranspiration, AWE is available water for evaporation, and NSS is near-surface storage, computed as $NSS = (AWE - AE) \times 0.45$ (Rushton, 2005). Recharge was generated only once SMD fell to zero or below.

2.4 HEC-HMS Model Setup, Parameter Scope and Calibration

The HEC-HMS model was parameterized using a digital elevation model (DEM) for basin delineation. Loss mechanisms were calculated using the SCS Curve Number (CN) method, and surface run-off transformation was modeled via the SCS Unit Hydrograph method. Baseflow processes were set to 'None' because observed continuous baseflow data were unavailable, restricting calibration parameters to CN, lag time (Tlag), and percentage imperviousness.

Because no operational hydrometric gauging station exists within the sub-basin catchment, HEC-HMS was calibrated against synthetic daily run-off generated by the SMB model for July 2024. Consequently, performance statistics, Nash–Sutcliffe Efficiency (NSE) and Coefficient of Determination (R^2), measure internal inter-model consistency rather than true field predictive skill.

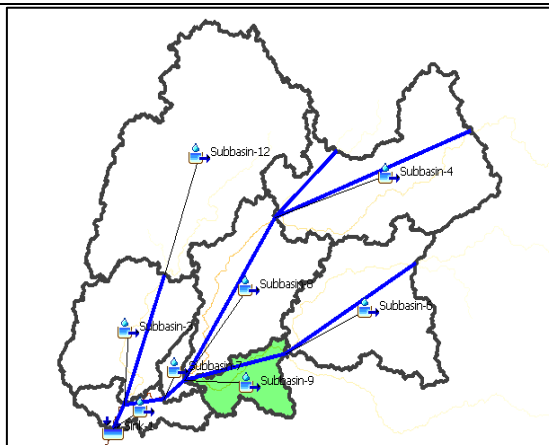


Figure 2.4: HEC-HMS Basin Model Schematic showing sub-basin delineation for the New Bussa catchment.

3. RESULTS AND DISCUSSION

3.1 Climatic Characteristics of the Basin

The Climatic analysis reveals that New Bussa recorded a mean annual rainfall of 1,100mm, with a mean annual temperature of 28.7 °C and PET exceeding 1500mm/yr, implying greater atmospheric water demand and, by extension, lower recharge potential, a pattern broadly consistent with climatic controls documented elsewhere in Nigeria (Shuaibu, 2025).

Table 3.1: Mean Climatic Analysis of New Bussa Area

Location	Mean Annual Rainfall (mm)	Mean Temp. (°C)	Wet-Season Rainfall (mm)	Dry-Season Rainfall (mm)	Relative Humidity (%)	PET (mm/yr)
New Bussa	1,100	28.7	970	130	60	1,560

3.2 Soil Physical Properties and Infiltration Potential

Analysis of New Bussa's soil samples reveals a Sandy Loam texture with a bulk density of 1.59 g/cm³. This texture class is highly typical of sandy loam, which favours moderate to rapid drainage (Niger Foods GIS, 2024). A bulk density of 1.59 g/cm³ aligns with regional soil studies in Niger State, where sand-dominated agricultural soils frequently exhibit densities ranging between 1.46 g/cm³ and 1.61 g/cm³ depending on crop cultivation and vegetative cover (Muhammad et al., 2025). Field capacity of 18.41% was obtained, and a wilting point of 8.2%, resulting in an available water capacity of 10.21% and Ksat of 11.1mm/yr respectively.

Table 3.2: Simulated Soil Properties of the New Bussa Area

LGA	Texture Class	Bulk Density (g/cm ³)	Field Capacity (%)	Wilting Point (%)	AWC FC-WP (%)	Ksat (mm/hr)
New Bussa	Sandy Loam	1.59	18.41	8.2	10.21	11.1

3.3 HEC-HMS Model Calibration

Six calibration trials were conducted using July 2024 daily data (Table 3.3). Trial 6 yielded the optimal inter-model fit with CN=40, Tlag=100 min, and 10% imperviousness, achieving an NSE of 0.52, an R² of 0.797, and an RMSE of 0.99.

A notable divergence was observed across trials between NSE and R² dynamics. For example, Trial 3 exhibited a high R² (0.87) alongside a poor NSE (0.14). This statistical behavior occurs because R² evaluates linear covariance regardless of systematic magnitude bias, whereas NSE heavily penalizes peak discharge offset errors and variance mismatches. Lowering the Curve Number to 40 in Trial 6 mitigated peak volume overestimations, aligning runoff volumes and optimizing NSE.

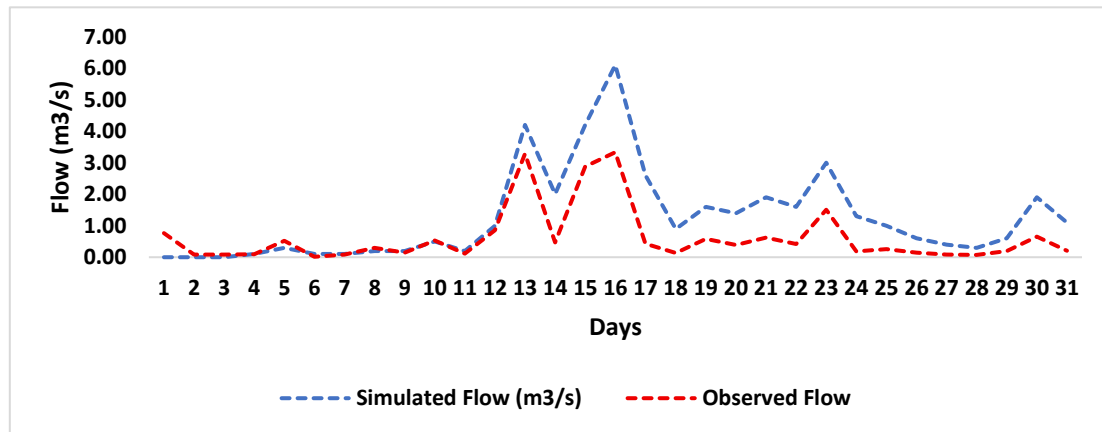


Figure 3.1: Comparison of measured flow (Python-Based Model) and simulated flow (HEC-HMS)

Table 3.3: HEC-HMS Calibration Trials (Curve Number, Lag Time and Imperviousness)

Trial	Curve Number	Imperviousness (%)	Lag Time (min)	NSE	R ²	RMSE
1	71	25	323.42	-1.83	0.42	1.34
2	75	20	250.81	-0.30	0.51	1.87
3	85	20	200.53	0.14	0.87	1.24
4	65	10	100.00	0.28	0.84	1.78
5	50	10	100.00	0.41	0.81	1.32
6	40	10	100.00	0.52	0.797	0.99

3.4 Annual Water Balance, 2020–2024

Over the five-year evaluation period (2020–2024), total precipitation reached 5,996.59 mm (Table 3.4). Mean annual runoff accounted for 273.96 mm/yr (22.8% of rainfall), whereas mean annual groundwater recharge was only 31.96 mm/yr (2.7%). Simulated recharge was zero (0.00 mm) for years (2021–2024) and occurred exclusively during 2020 (159.81 mm).

This zero-recharge phenomenon illustrates the rigid threshold control inherent to the root-zone moisture balance framework. Recharge is triggered only after accumulated evapotranspiration deficits are completely satisfied ($SMD=0$). Sensitivity testing confirms that assuming a deep rooting depth ($Z_r=0.9$ m) increases overall soil storage capacity (TAW), requiring substantial cumulative wet-season rainfall (such as the 1,715.80 mm recorded in 2020) to break the threshold. While localized preferential flow through cracked regolith may cause minor real-world annual recharge, the model accurately reflects a regime where matrix percolation is highly episodic.

Table 3.4: Annual Rainfall, Runoff and Groundwater Recharge (2020–2024)

Year	Rainfall (mm)	Runoff (mm)	Groundwater Recharge (mm)
2020	1,715.80	482.28	159.81
2021	989.07	205.40	0
2022	1,281.44	267.60	0
2023	1,160.59	240.34	0
2024	849.69	174.20	0
Total	5,996.59	1,369.81	159.81

Table 3.5: Mean Annual Values of the Hydrological Parameters (2020–2024)

Parameter	Annual Average (mm)	Share of Rainfall (%)
Rainfall	1,199.32	100.0
Runoff	273.96	22.8
Groundwater Recharge	31.96	2.7

3.5 Synthesis and Methodological Limitations

The results highlight a runoff-dominated hydrological system where groundwater replenishment is minimal and episodic. However, key limitations must frame the interpretation of these findings:

1. **Calibration Circularity:** Calibrating HEC-HMS against SMB-derived runoff verifies conceptual alignment between models but does not substitute for field-observed streamflow validation.
2. **Temporal Window:** Calibrating across a single month (July 2024) restricts parameter robustness across varying multi-year antecedent moisture states.
3. **Excluded Baseflow:** Omitting subsurface baseflow mechanisms limits the model's capacity to simulate low-flow regimes accurately.

Consequently, the numerical estimates (e.g., 2.7% annual recharge fraction) should be interpreted as model-derived baseline hypotheses requiring empirical piezometric and tracer-based validation.

4. CONCLUSION

This study integrated SMB and HEC-HMS modelling to evaluate recharge dynamics in the New Bussa sub-basin. The hydrological regime is runoff-dominated (22.8% of rainfall), with groundwater recharge being episodic (2.7% long-term mean) and reliant on extreme rainfall events that satisfy root-zone storage capacity. Because conclusions derived from New Bussa cannot be directly extrapolated across the entire Middle Niger region without accounting for local hydrogeological heterogeneity, caution is advised in abstraction planning. Groundwater development strategies should be combined with rainwater harvesting and managed aquifer recharge schemes. Future research must prioritize establishing physical streamflow gauging and multi-year piezometric monitoring to eliminate model circularity.

5. REFERENCES

- Cuthbert, M. O., Gleeson, T., Bierkens, M. F. P., Ferguson, G., & Taylor, R. G. (2023). Defining renewable groundwater use and its relevance to sustainable groundwater management. *Water Resources Research*, 59(9), e2022WR032831.
- Healy, R. W., & PG Cook (2002). Using underground water levels to estimate recharge. *Hydrogeology journal*, 2002-Springer.
- Muhammad, S. A., Ahmed, S., Inuwa, G., Muhammed, M., Muhammad, A. E., & Lawal, B. (2025). Impact of land degradation on physical properties of soils in Mokwa Local Government Area, Niger State, Nigeria. *Journal of Agricultural and Environmental Science Research*, 14(1), 112–125. <https://hummingbirdjournals.com/jaesr/article/view/413>
- Müller, E. V. (2023). Analysis of forest-specific ecosystem services with regard to water balance components: Runoff and groundwater recharge in the forest.
- Niger Foods GIS. (2024). Soil texture of Niger State maps. Niger Foods GIS Database. <https://nigerfoodsgis.com.ng/soil-texture-of-niger-state-pdf-maps/>
- Ogunbode, T. O., Oyebamiji, V. O., Akinkuolie, A. T., Adekiya, O. A., Oyelami, A. A., Taiwo, T. M., & Paul, I. I. (2024). Evaluating water security in sub-Saharan Africa: Examining a case study of water supply inventory, accessibility, and predictability on Iwo, Nigeria. *World Water Policy*, 10(4), 1223-1242.
- Olaleye, I. M., Ige, O. O., & Oyeleke, T. A. (2025). Assessment of aquifer potential in parts of Southern Bida Basin, Southwestern Nigeria. *International Journal of Energy and Water Resources*, 9(3), 1269-1284.
- Rushton, K. R. (2005). Estimating recharge for British aquifers. *Water and Environment Journal*, 19(2), 115-124
- Rushton, K. R. Eilers, V. H. M. and Carter, R. C. (2006). Improved Soil Moisture Balance Methodology for Recharge Estimation. *Journal of Hydrology*, 318: 379-399.
- Scanlon, B. R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., ... & Zheng, C. (2023). Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Environment*, 4(2), 87-101.
- Shaikh, M., & Birajdar, F. (2024). Groundwater and ecosystems: understanding the critical interplay for sustainability and conservation. *EPRA International Journal of Multidisciplinary Research*, 10(3), 181-186.
- Shuaibu, A., Kalin, R. M., Phoenix, V., Banda, L. C., & Hinton, R. G. K. (2025). Investigation of groundwater recharge in the transboundary Komadugu-Yobe basin Nigeria via stable isotopes of O¹⁸ and H² and comparison with the wider Sahel, Africa. *Science of The Total Environment*, 994, 180043. <https://doi.org/10.1016/j.scitotenv.2025.180043>