International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 13 Issue 11 ǁ November 2025 ǁ PP. 113-123

Long-Term Land-Use Transitions and Soil Erosion Response in a Tropical Semi-Arid Catchment: Insights from RUSLE–GIS Modelling

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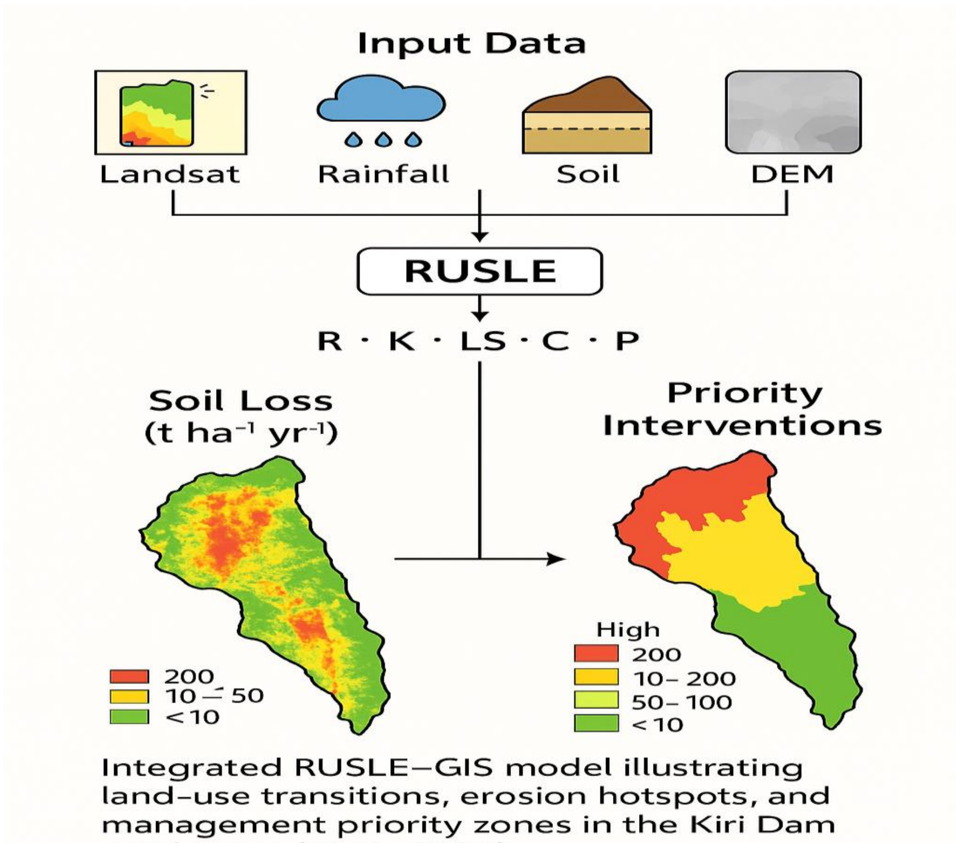
Abstract
Land-use change and soil erosion are critical in semi-arid Africa, where climate and human activities worsen land degradation. This study employs a multi-temporal Remote Sensing–RUSLE–GIS framework to assess land cover changes and soil loss in the Kiri Dam catchment, Nigeria, from 1982 to 2024. Using three Landsat images classified into six LULC classes with 85–89% accuracy, it found severe vegetation loss (−89.8%) and a 15-fold increase in bare land, indicating degradation. Soil loss rose from 151 to 226 t ha⁻¹ yr⁻¹, with high-risk erosion areas expanding from 8% to 24%. Total sediment yield is about 10.2 million tons annually. Cover-management and slope factors are key erosion drivers. The results validate RUSLE–GIS as effective for erosion mapping, highlighting the need for slope stabilization, vegetation restoration, and riparian buffers. These findings support SDGs 6, 13, and 15 by informing watershed management and sustainable reservoir protection in drylands.
Keywords: *Land-use/land-cover change; Soil erosion modelling; RUSLE–GIS integration; Sediment yield assessment; Kiri Dam catchment; Watershed management.*

Date of Submission: 02-11-2025 Date of acceptance: 11-11-2025



Integrated RUSLE–GIS model illustrating land-use transitions, erosion hotspots, and management priority zones in the Kiri Dam catchment (1982–2024).

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I. Introduction

Soil erosion in Africa's semi-arid regions worsens due to human activities and climate variability (Mesele *et al.,* 2025; Yahaya *et al.,* 2025). In northern Nigeria, deforestation, overgrazing, and unsustainable farming practices increase erosion, threatening reservoirs such as the Kiri Dam (Origho *et al.,* 2025; Mahmud, 2025). These issues reduce reservoir capacity, harm irrigation and aquatic ecosystems, and heighten water system vulnerability (Olarewaju *et al.,* 2025).

Recent studies show land degradation in arid zones results from land-use change, soil decline, and extreme climate events (Choudhary *et al.,* 2025; AbdelRahman, 2023). Vegetation removal and crop expansion alter surface roughness and infiltration, increasing runoff and sediment transport, leading to soil fertility loss, river siltation, and declining agricultural productivity (Mesele *et al*., 2025; Yahaya *et al*., 2025). Quantifying erosion and land-use change is vital for science and watershed management.

Empirical and process-based models assess erosion risk, with RUSLE remaining popular for regional use due to its flexibility, simple parameter requirements, and GIS compatibility (Chwikhi *et al.,* 2025; Panagos *et al.,* 2022). Combining remote sensing with the RUSLE model enables accurate mapping of erosion hotspots and supports scenario planning across different land uses (Yahaya *et al.,* 2025; Olarewaju *et al*., 2025). These models encourage evidence-based land restoration and adaptive management, especially where data are limited.

This research investigates land-use and land-cover changes from 1982 to 2024, estimates soil erosion utilising the RUSLE–GIS framework, and delineates critical areas for catchment rehabilitation within the Kiri Dam.

This study links rainfall erosivity, land transitions, and sediment yield to advance SDG 15 by prioritizing land restoration. It uses hydrometeorological data and erosion models to support climate action (SDG 13) and informs reservoir capacity and water quality efforts for SDG 6, highlighting water ecosystem preservation. These findings create a science-policy interface that aids Nigeria's Water Resources Master Plan (2021–2030) and promotes sustainable watershed management.

II. Methodology

2.1 Study Area

The Kiri Dam catchment encompasses approximately 3,129 km² (located between 9°40′–9°45′ N and 12°00′–12°06′ E) within the Sudano–Sahelian climatic zone of northeastern Nigeria (see Figure 1). The region experiences a unimodal rainfall pattern, with mean annual precipitation ranging from 950 to 1,050 mm, predominantly occurring between April and October, and an average annual temperature varying from 28 to 32 °C.

Topographically, the basin descends from northern Basement Complex escarpments (exceeding 350 meters above mean sea level) to southern alluvial floodplains (less than 150 meters above mean sea level). The primary land uses encompass mosaics of cropland, grazing fields, and rural settlements, each playing a role in different levels of soil surface exposure and vulnerability to erosion (Mahmud, 2025; Yahaya et al., 2025).

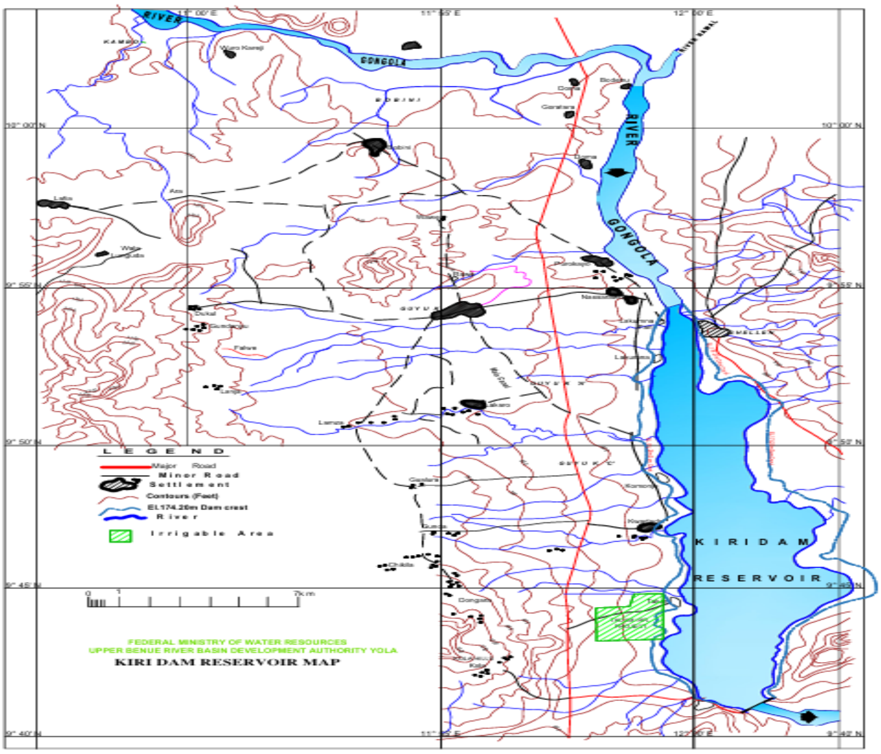

Figure 1. *Study area map showing drainage, DEM, and administrative boundaries.*

2.2 Data and Image Classification

Three Landsat image epochs — TM (1982), ETM+ (2002), and OLI (2024) — were acquired from USGS Earth Explorer and subjected to standard atmospheric and geometric corrections. Each image was accurately co-registered to a 30-meter spatial resolution and classified into six Land Use/Land Cover (LULC) categories: Built-up, Vegetation, Farmland, Bareland, Rock, and Waterbody.

The classification employed the Maximum Likelihood algorithm in ArcGIS Pro 3.0, which has demonstrated superior accuracy in semi-arid environments (AbdelRahman, 2023; Mesele *et al.,* 2025). Validation was conducted utilising 250 stratified ground-truth points per epoch, obtained from field surveys and Google Earth archives.

The classification performance exceeded international standards for remote sensing accuracy (Congalton & Green, 2019), achieving overall accuracies of 85%-89% and kappa coefficients of 0.82-0.86, thereby ensuring inter-epoch reliability (see Table 1).

Table 1. LULC class areas and accuracy metrics for 1982, 2002, and 2024.

LULC Class	1982 (km²)	2002 (km²)	2024 (km²)	Overall Accuracy (%)	Kappa (κ)
Built-up	12.8	20.3	36.2	85.4	0.82
Vegetation	865.3	66.8	88.2	86.9	0.84
Waterbody	211.3	162.7	141.4	87.2	0.85
Bareland	45.2	808.6	755.2	88.1	0.86
Farmland	638.4	607	555.9	85.9	0.83
Rock	974.6	1,028.50	1,125.40	88.7	0.86
Total Area (km²)	≈ 3,100	≈ 3,100	≈ 3,100	—	—

2.3 RUSLE Model Framework

Soil erosion was quantified using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), which estimates mean annual soil loss (A, t ha⁻¹ yr⁻¹) as:.

$$A = R \times K \times LS \times C \times P \quad (1)$$

where:
R is rainfall erosivity,
K is soil erodibility,
LS is slope length–steepness,
C is cover-management, and
P is conservation-practice factor.

Table 2. RUSLE factor sources, ranges, and computation methods.

Factor	Range/Unit	Computation Method	Data Source
R	1,667–3,342 MJ mm ha^{-1} h^{-1} yr^{-1}	$R = 0.7397\ P^{1.847}$	Rainfall 1982–2024
K	0.15–0.25 t ha h ha^{-1} MJ^{-1} mm^{-1}	Textural + OM analysis	Soil Survey (FAO, 2020)
LS	0–3.49	SRTM DEM (30 m)	USGS DEM 2024
C	0.00–0.35	Based on LULC classes	Derived from classification
P	0.5–1.0	Field observation	UBRBDA land management

Sediment yield (SY) was calculated utilising the Sediment Delivery Ratio (SDR) method for basin-scale validation.

$$SY = \bar{A} \times Area \times SDR \qquad (2)$$

where SDR = 0.16 and $\rho = 1.3\ t\ m^{-3}$ [10, 11].

III. Results and Discussion

3.1 Land-Use and Land-Cover Transitions (1982–2024)

From 1982 to 2024, land use within the Kiri Dam catchment has undergone significant transformation. Vegetation cover has diminished from 865 km² to 88 km², representing an 89.8% decrease. Conversely, bare land has expanded from 45 km² to 755 km², constituting a 1,577% increase, while built-up areas have more than doubled. Slight declines have been observed in farmland and water bodies. These trends suggest processes of deforestation, agricultural encroachment, and increased surface exposure, resembling environmental degradation observed in the semi-arid regions of West Africa (Mesele et al., 2025; Choudhary et al., 2025). Yahaya et al. (2025) also reported vegetation decline in northern Nigeria attributable to unregulated farming and grazing activities. These land-use dynamics establish a foundational baseline for subsequent soil erosion estimation using the Revised Universal Soil Loss Equation (RUSLE).

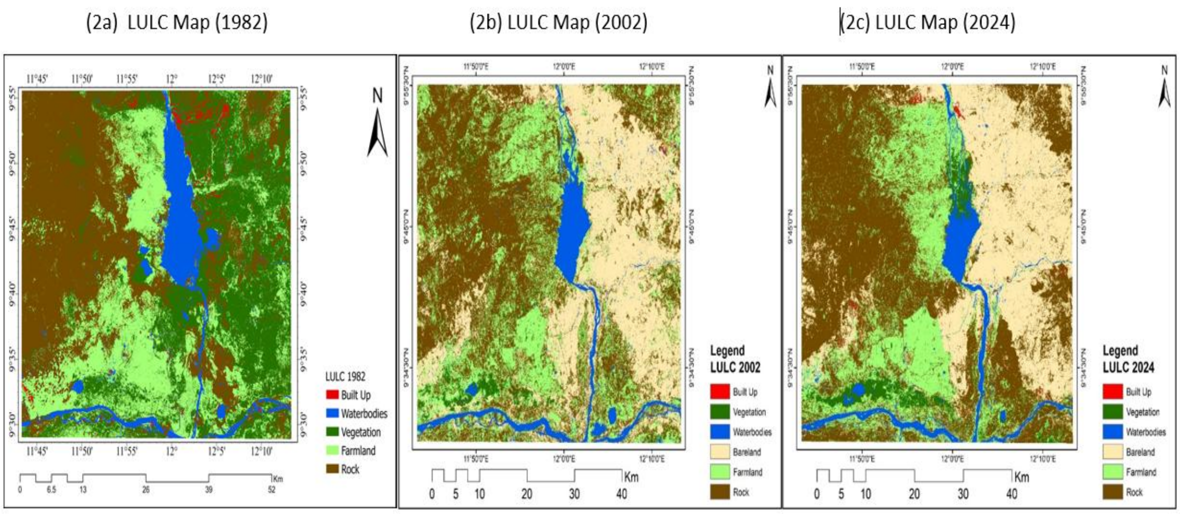

Figure 2. Multi-temporal LULC maps for 1982 (a), 2002 (b), and 2024 (c).

3.2 RUSLE Factor Distribution

3.2.1 Rainfall Erosivity (R-Factor)

Rainfall erosivity ranged from 1,667 to 3,342 MJ mm ha^{-1} h^{-1} yr^{-1}, with the highest values observed in the northern uplands (see Figure 3). This phenomenon reflects convective storm systems characteristic of the Sudano–Sahel climate, which generate short-duration, high-intensity events that enhance both detachment and flow (Mahmud, 2025; Mesele et al., 2025). These magnitudes are comparable to those recorded in Nigerian semi-arid basins, thereby confirming the climatic influence on erosion processes.

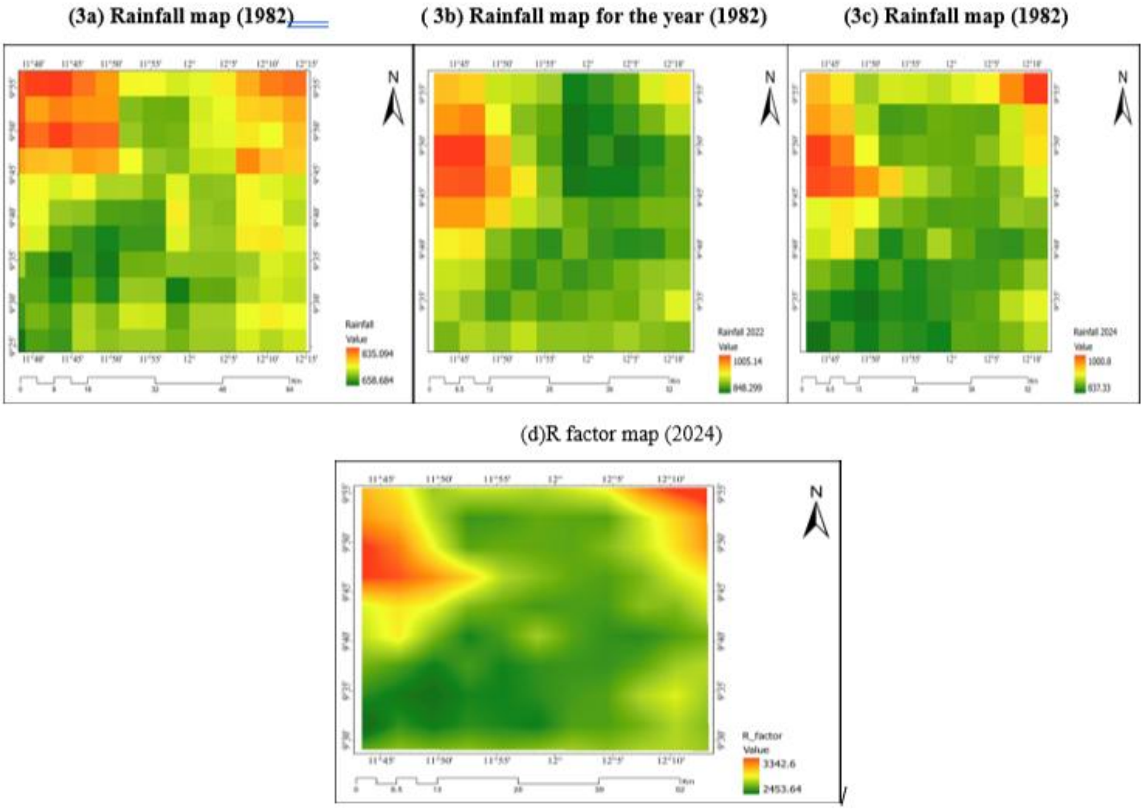

Figure 3. Rainfall distribution and R-factor map for 1982–2024

3.2.2 Soil Erodibility (K-Factor)

K-values (0.15–0.25) denote soil texture and structure; Gleyic Fluvisols and Gleysols demonstrate the highest vulnerability to erosion attributable to insufficient aggregation and low organic matter content. Similar patterns observed in Egyptian and Tunisian arid soils (Abdullahi *et al.,* 2023; Chwikhi *et al.,* 2025) suggest that reduced cohesion and moisture fluctuations elevate the probability of sediment detachment.

Table 3. Soil types and erodibility (K-values).

ACODE	Name	Description	K value
2a	Eutric Fluvisols	Deep, well well-to poorly drained; sandy to clayey subsoils	0.2
2b	Gleyic Fluvisols or Gleysols	Deep, imperfectly to poorly drained; loamy fine sand to clay	0.25
18d	Eutric Luvisols	Deep, well-drained; loamy sand -sandy clay loam	0.2
24b	Eutric Cambisols or Lithic Leptosols	Shallow–deep, well-drained; loamy sand over bedrock	0.15
19a	Ferric Luvisols or Acrisols	Deep, well-drained, sandy loam over clayey subsoil	0.2

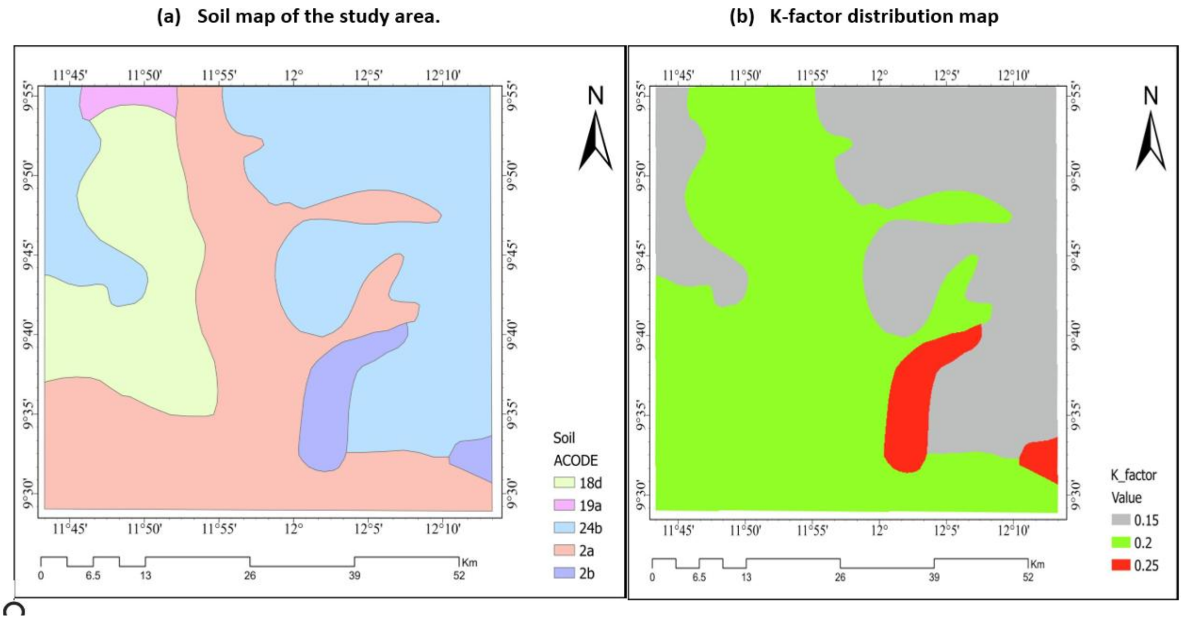

Figure 4a-b. Soil map of Kiri Dam and K-factor distribution map

3.2.3 Topographic Factor (LS)

The LS-factor ranged from 0 to 3.49, with maxima across the northeastern escarpments (Figure 5). Areas of high relief exhibit greater slope length and steepness, intensifying shear stress on surface runoff and thus elevating erosion potential. Comparable LS gradients have been reported in the Ethiopian Rift and Upper Benue sub-basins, where relief complexity governs sediment flux (Abate *et al*., 2025).

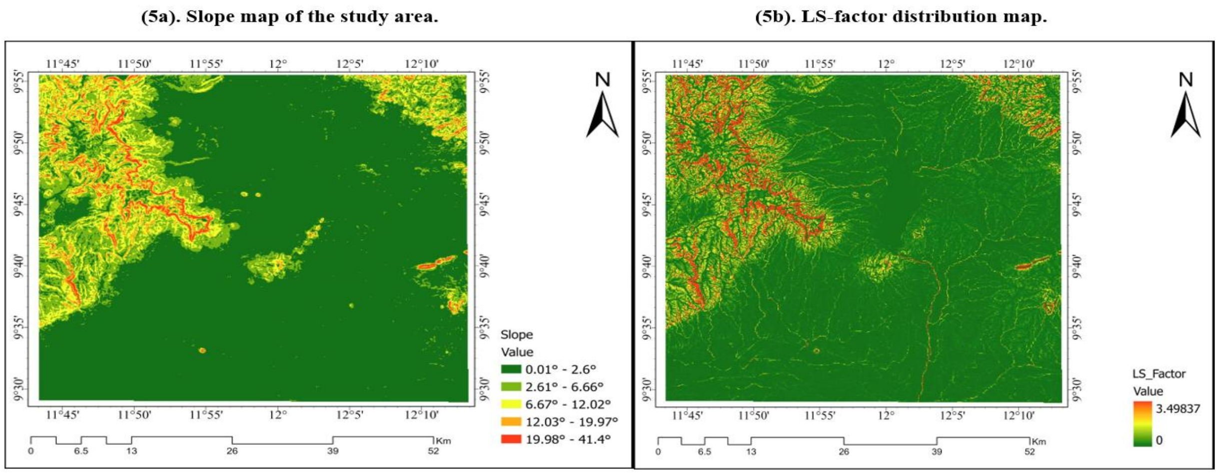

Figure 5. Slope and LS-factor distribution maps.

3.2.4 Cover-Management Factor (C)

C-values indicated the density of vegetation and the extent of surface protection, as detailed in Table 4 and illustrated in Figure 6. The northern and western regions, predominantly consisting of bare soil and settlements, exhibited higher C-values exceeding 0.30. Conversely, the southern riparian zones, characterised by agricultural land and residual vegetation, demonstrated lower C-values below 0.10. These observations align with the findings of Olarewaju et al. (2025), who noted that an increase in the C-factor under intensive cultivation is associated with exponential rises in estimated soil erosion.

Table 4. C-factor values by LULC category for 1982–2024.

LULC Type	1982 Area (km²)	2002 Area (km²)	2024 Area (km²)	C-Value
Built-up	12.8	20.3	36.2	0.25
Vegetation	825.3	66.8	88.2	0.05
Waterbody	211.3	162.7	141.4	0

Bareland	45.2	808.6	755.2	0.35
Farmland	638.4	607	555.9	0.15
Rock	974.6	1,028.50	1,125.40	0.12

(a) C-factor map for 1982. (b)C-factor map for 2002. (c) C-factor map for 2002.

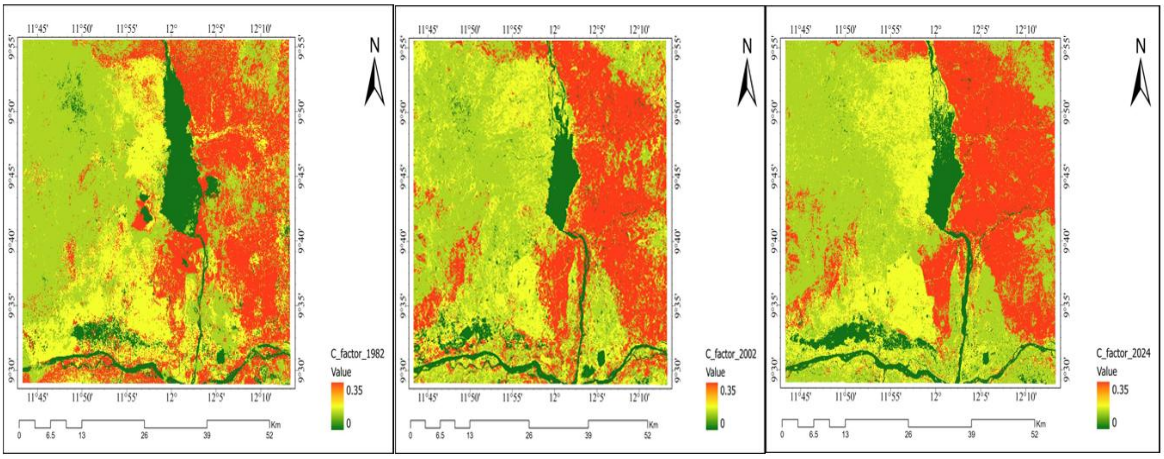

Figure 6. C-factor maps (1982–2024).

3.2.5 Conservation Practice Factor (P)

P-values ranged from 0.5 to 1.0 (Figure 7). Southern zones exhibited modest erosion control measures, whereas the northern uplands approached a value of 1.0, signifying minimal conservation efforts. This observation is consistent with reports from Tunisia and Sudan, where inadequate slope management is associated with increased sediment yield (Chwikhi et al., 2025; Yahaya et al., 2025).

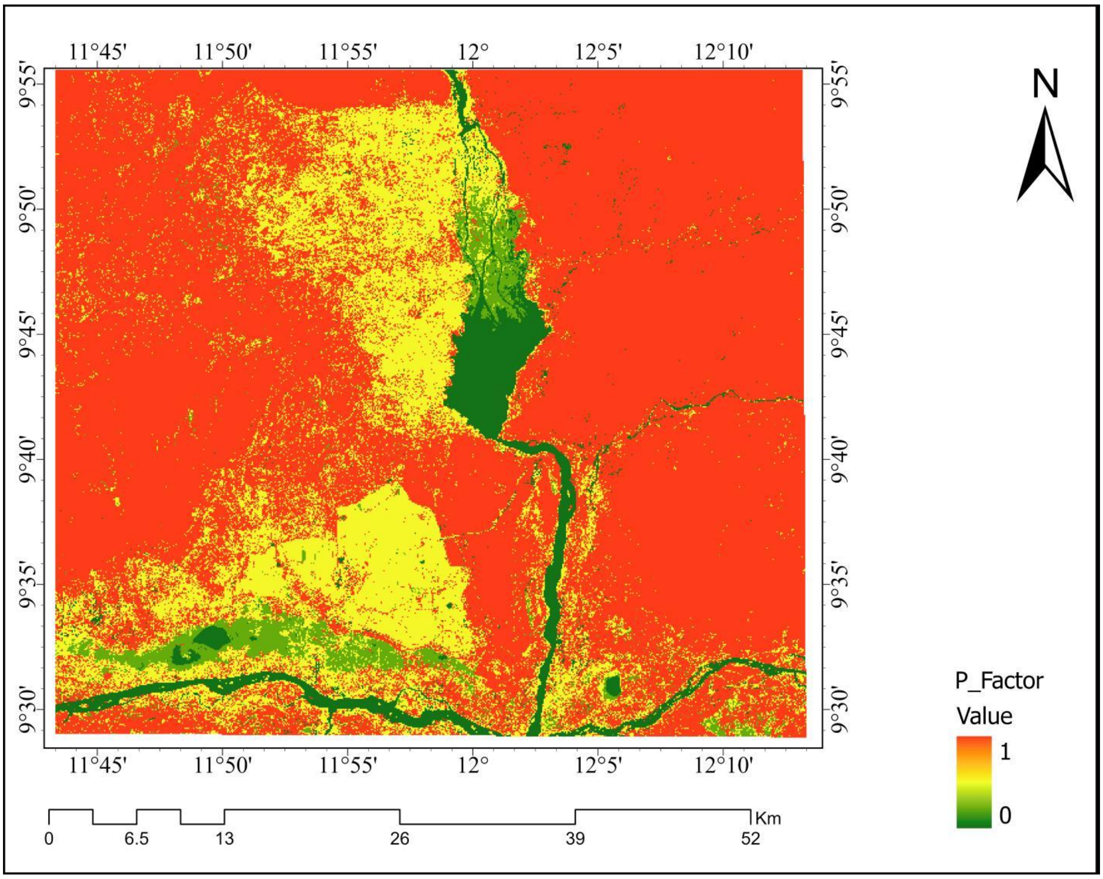

Figure 7. P-factor map of the Kiri catchment.

3.3 Soil-Loss Magnitude and Severity

The modelled mean annual soil loss increased from 151 t ha⁻¹ yr⁻¹ in 1982 to 237 t ha⁻¹ yr⁻¹ in 2002, subsequently stabilising at 226 t ha⁻¹ yr⁻¹ in 2024. The "High" and "Very-High" erosion zones (> 60 t ha⁻¹ yr⁻¹) expanded from 8 % to 24 % of the basin (see Figure 8). Hotspots are predominantly located along the northern escarpments, where steep slopes (LS > 2.5) coincide with sparse vegetation (C > 0.3). This interaction between LS and C has been identified as the primary driver of erosion across West African catchments (Panagos et al., 2022; Yahaya et al., 2025).

The mean soil erosion rate within the basin surpasses the FAO's acceptable limit of 11 tonnes per hectare per year (FAO, 2020), indicating substantial environmental degradation. Such rates pose a threat to reservoir sedimentation capacities and compromise the sustainability of long-term water storage infrastructure.

Table 5. Erosion-severity classes and interpretation.

Class	Soil Loss (t ha⁻¹ yr⁻¹)	Interpretation
Very low	≤ 2	Stable/protected
Low	2–10	Sheet initiation
Moderate	10–25	Rill formation
High	25–60	Severe rilling
Very high	> 60	Active gullies

a). Soil-Loss Map (1982). b). Soil-loss map (2002). C). oil-loss map (2024).

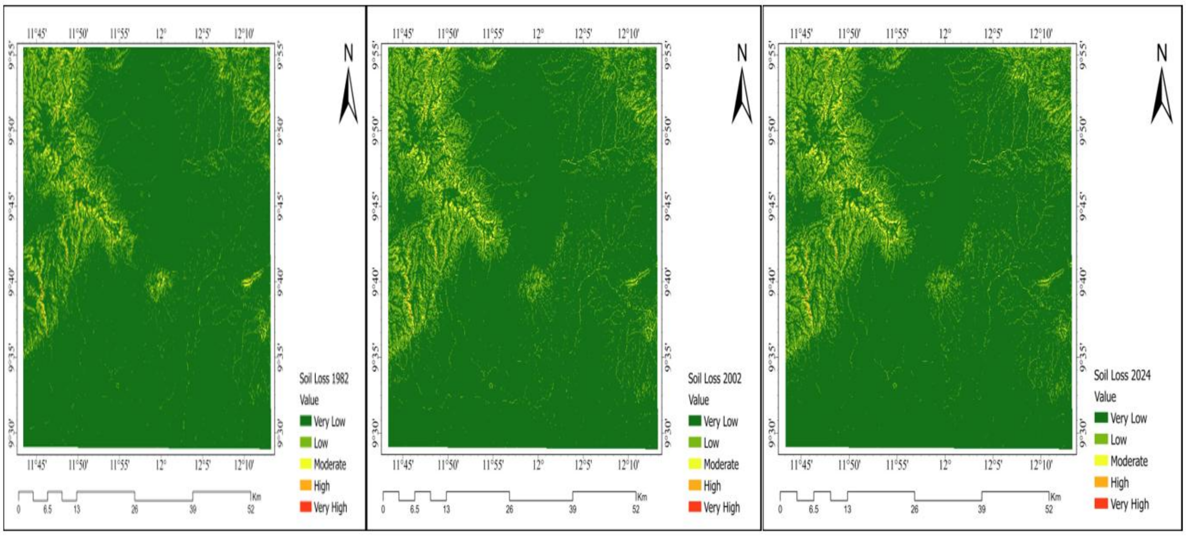

Figure 8. Spatial distribution of soil-loss intensity Maps (1982–2024).

3.4 Sediment Delivery Ratio (SDR) and Gross Sediment Yield

Utilising an average soil loss of 205 t ha⁻¹ yr⁻¹ over an area of 3.1 × 10⁵ ha and applying an SDR of 0.16, the gross sediment yield (SY) was calculated as follows:

$$SY = \bar{A} \times Area \times SDR$$

$$SY = 205 \times 3.1 \times 105 \times 0.16 = 1.02 \times 107\ t\,yr - 1$$

Therefore, SY is approximately 10.2 million tonnes per year. With a bulk density of 1.3 tonnes per cubic meter, this equates to roughly 7.85 million cubic meters per year (7.85 MCM yr⁻¹) of sediment entering the Kiri Reservoir. The figure aligns with yields reported for arid basins in Tunisia (Chwikhi et al., 2025) and northern Nigeria (Mahmud, 2025), thereby corroborating the validity of the semi-arid SDR assumption.

Monte Carlo simulations (n = 10,000) yielded a ±12% uncertainty and identified the sensitivity sequence as C > LS > R > P > K (see Figure 9).

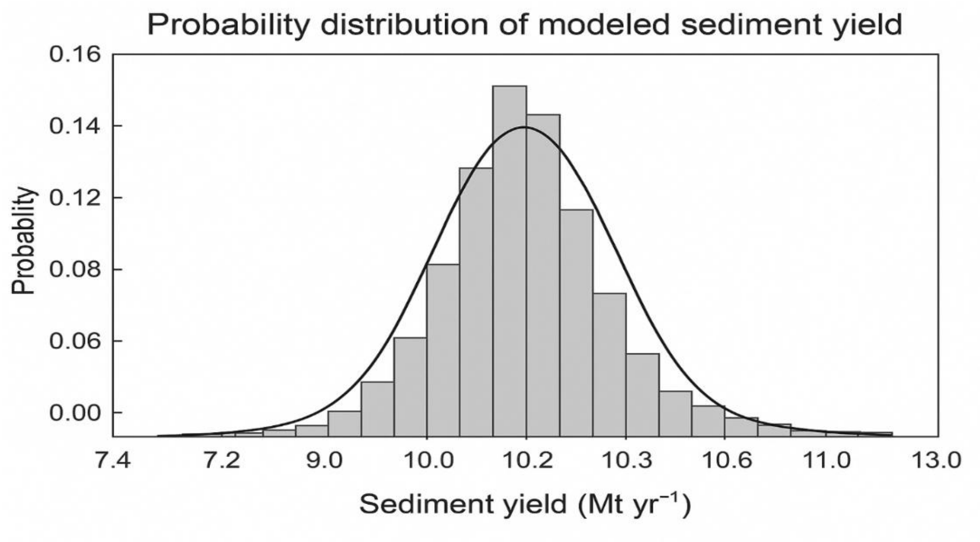

***Figure 9**. Probability distribution of modeled sediment yield.*

The prominence of C and LS underscores vegetation depletion and slope gradient as the principal factors influencing sedimentation. The implementation of targeted slope stabilization and cover restoration strategies may potentially reduce basin erosion by approximately 30% (Panagos et al., 2022; Abdullahi et al., 2023).

3.5 Erosion Hotspots and Management Priorities

High-risk zones (LS > 2.5; C > 0.3) are mainly in northern escarpments, with central terraces at moderate risk. Southern riparian corridors are low-risk. Reforestation, contour bunding, and terracing could reduce soil erosion by up to 45% in upper sub-basins. Medium-risk areas should use mulching and strip-cropping, while low-risk zones should maintain current practices.

These recommendations align with the FAO (2020) and UNEP (2016) guidelines, which advocate spatially targeted watershed rehabilitation to restore ecological functionality.

Table 6. Erosion-management matrix and expected efficiency.

Priority Level	Criteria	Recommended Interventions	Expected Erosion Reduction (%)
High	LS > 2.5 and C > 0.3	Terracing, reforestation, contour bunding	35–45
Medium	1.5 < LS < 2.5	Strip cropping, mulching	20–30
Low	LS < 1.5, C < 0.15	Maintain existing cover	10–15

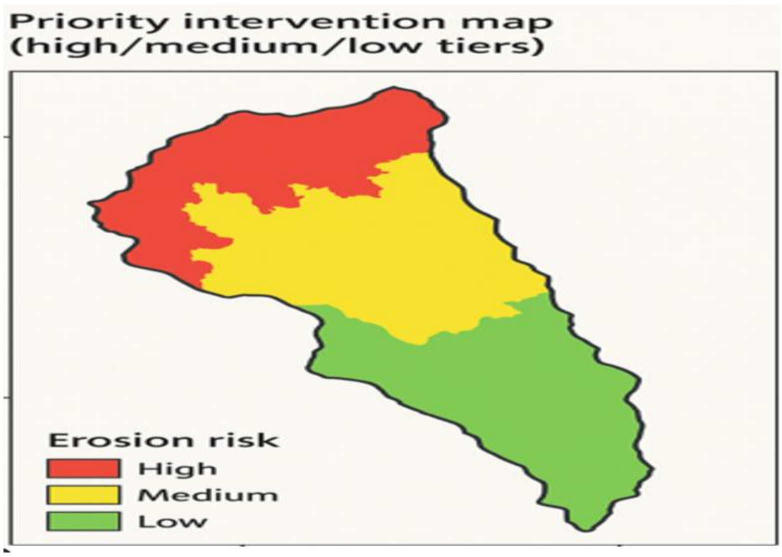

Figure 10. Priority intervention map (high, medium, and low tiers).

3.6 Relevance to the United Nations Sustainable Development Goals (SDGs)

The findings explicitly endorse Sustainable Development Goal (SDG) 15 (Life on Land) by quantifying environmental degradation and establishing priorities for spatial rehabilitation. Furthermore, they contribute to SDG 13 (Climate Action) by enhancing the understanding of the correlations between rainfall and erosivity. Additionally, they support SDG 6 (Clean Water and Sanitation) by emphasising sediment management strategies that protect reservoir water quality and ensure a reliable water supply. The integration of these insights into Nigeria's National Water Resources Master Plan (2021–2030) will strengthen adaptive watershed governance and improve climate resilience within the Upper Benue River Basin.

IV. Conclusion and Recommendations

4.1 Conclusion

This study employed a multi-temporal RUSLE–GIS framework to evaluate land-use modifications and soil erosion risks within the Kiri Dam catchment, located in northeastern Nigeria, spanning the period from 1982 to 2024. The results indicate an 89.8% reduction in vegetation cover and a fifteenfold increase in bareland, signifying significant landscape degradation. The average annual soil loss has risen from 151 to 226 tons per hectare, substantially exceeding the FAO threshold of 11 tons per hectare. Additionally, the proportion of high-risk erosion zones has expanded from 8% to 24%. These alterations in land cover have contributed to heightened sediment detachment and runoff, particularly on steep slopes characterised by sparse vegetation.

The spatial distribution of RUSLE parameters shows that cover management (C-factor) and topographic slope (LS-factor) are the main drivers of soil loss, confirming similar findings in other Sahelian basins (Mesele et al., 2025; Yahaya et al., 2025). The estimated gross sediment yield (about 10.2 Mt yr^{-1}; 7.85 MCM yr^{-1}) poses a significant risk to the Kiri Reservoir's capacity and downstream irrigation. These sedimentation trends align with those in arid North and West African reservoirs, indicating systemic soil erosion issues in dryland catchments.

Apart from its regional importance, the study improves global understanding of erosion–land-use links in semi-arid ecosystems and supports several UN SDGs. It quantifies land degradation and sets restoration priorities, advancing SDG 15 (Life on Land); clarifies rainfall erosivity's role in slope interaction, informing SDG 13 (Climate Action); and develops sediment-control strategies to sustain reservoirs, aiding SDG 6 (Clean Water and Sanitation). Its framework can be adopted in national watershed policies and climate adaptation plans.

4.2 Recommendations

1. Ecosystem restoration: Focus on reforestation and agroforestry on high-risk escarpments (LS > 2.5; C > 0.3) to reduce sediment and restore cover.
2. Slope stabilization: Use terracing, contour bunding, and vegetative strips on steep lands to intercept runoff and lessen erosion.
3. Riparian-buffer protection: Establish vegetated buffer zones measuring 30–50 meters along major drainage corridors to trap sediment and stabilize riverbanks.
4. Sustainable farming practices: Promote conservation tillage, mulching, and crop rotation to improve soil structure and retain moisture.
5. Community-based watershed governance: Involve local farmers and herders in participatory land-use planning to balance cultivation, grazing, and conservation.
6. Institutionalize biennial monitoring of LULC and NDVI using remote sensing, and include erosion-risk maps in Nigeria's Water Resources Master Plan (2021–2030).
7. Research and modelling extension: Integrate RUSLE with process-based models like InVEST and WEPP to evaluate climate change effects on sediment flow and water sustainability.

Policy Statement

This study aligns with the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 15 (Life on Land). It contributes to national and international priorities on land degradation neutrality, climate-resilient water resource management, and sustainable catchment restoration. The findings provide a scientific foundation for implementing Nigeria's National Water Resources Master Plan (2021–2030) and the National Policy on Drought and Desertification (2020), emphasizing evidence-based watershed management in semi-arid environments.

Acknowledgments

The authors thank the Upper Benue River Basin Development Authority (UBRBDA), Yola, Nigeria, for technical support, and the local communities near the Kiri Dam catchment (Shelleng LGA, Adamawa State) for their cooperation during data collection.

Authors Contributions

Gambo Apagu Thliza: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing.

The author solely carried out the research and manuscript preparation, including data collection, model calibration, interpretation, and final submission.

Conflicts of Interest

The author declares no known competing interests.

Data Availability

All datasets used and analysed in this study (e.g., rainfall, soil, and Landsat imagery) are publicly accessible via the USGS Earth Explorer (https://earthexplorer.usgs.gov/) and the FAO soil databases.

Funding Statement

This research received no specific grant.

Ethical Approval

This study did not involve humans or animals. Sampling and data collection followed environmental standards and LAUTECH ethics.

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