Assessment of Rainfall Variability and Its Impact on Soil Erosion Risk Using Rainfall Erosivity in Kwara State, Nigeria

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Abstract

Rainfall is the primary driver of water-induced soil erosion, and its erosive power is quantified by rainfall erosivity. Rainfall in Kwara state, Nigeria is believed to be the major cause of erosion. Hence, this study assessed the spatio-temporal distribution of rainfall and rainfall erosivity in Kwara State, Nigeria, for the period 2000 to 2025, with the aim was of determining the pattern of rainfall, the pattern of its erosive power, and the linkage between both parameters to soil erosion and soil conservation planning. Rainfall data and Rainfall Erosivity maps for six epochs, 2000, 2005, 2010, 2015, 2020 and 2025, were acquired and analyzed using geospatial techniques. Nine sample points (S1-S9) were extracted across the state to quantify trends. The Rainfall Erosivity (R-Factor) in RUSLE was used to measure the power of rainfall to cause soil erosion. Trend analysis, scatter plot and linear regression were used to establish the relationship between rainfall (RNF) and erosivity (ER). Results revealed a consistent northwest to southeast gradient for both parameters. The northern LGAs of Baruten, Kaiama and Patigi consistently recorded Very Low to Low rainfall and Low erosivity, with values as low as 566.33 MJ mm ha-1 h-1 yr-1 in 2000, while the southern LGAs of Ekiti, Oke-Ero, Isin, Ifelodun, Irepodun and Offa consistently recorded High to Very High rainfall and High erosivity, peaking at 1277.56 MJ mm ha-1 h-1 yr-1 in 2010. Temporally, both parameters peaked in 2010, with state average rainfall of 1819.57 mm and average erosivity of 1014.47, and were lowest in 2000. A perfect positive linear relationship was established with the equation ER = 0.562 x RNF - 8.1, proving that rainfall directly controls erosion risk. The study also revealed a baseline shift, where the minimum erosivity in 2025 (693.7) was higher than the maximum in 2000 (749.05), indicating increasing

rainfall intensity. The study concludes that Kwara State is becoming more erosive and that southern Kwara is the erosion hotspot requiring urgent conservation measures.

Keywords: Rainfall, Rainfall Erosivity, R-Factor, RUSLE, Spatio-temporal, Kwara State

Introduction

Rainfall erosivity (ER) serves as the primary climatic driver governing both initial soil particle detachment and subsequent sediment transport, together they constitute the fundamental physical processes that dictate the overall spatial and temporal risk of soil erosion within a given watershed (Nearing et al.,2017). The magnitude of rainfall erosivity reflects the kinetic energy imparted by falling raindrops; when high-intensity rainfall hits unprotected topsoil (Carollo et al., 2018), it disaggregates soil structural units through splash action, sealing surface pores and severely reducing infiltration capacity (Salles et al., 2000; Carollo et al., 2018). This drop in permeability rapidly generates overland flow and sheet runoff, which mobilizes detached particles and routes them downslope into local drainage channels (Batumalai et al., 2023).

The erosion process driven by rainfall operates primarily through two coupled mechanical pathways: Splash Detachment which is when falling raindrops collide with the bare soil surface, their kinetic energy is transferred to the soil matrix. This impact breaks apart soil aggregates, detachment individual particles, and seals surface micropores (Nearing et al., 2017). Runoff shear Stress and transport which occurs when rainfall intensity exceeds the infiltration capacity of the soil, excess water accumulates as overland flow. The shear stress exerted by this moving fluid mobilizes the previously detached particles and routes them downslope through sheet, rill, and gully networks. Because erosivity reflects both the impact force of falling drops and the volume of generated surface runoff, static total precipitation amounts alone are insufficient to predict soil loss. Instead, erosivity is fundamentally dependent on storm intensity and raindrop kinetic energy (Brodowski, 2013; Li et al 2017).

In an agro-based state like Kwara, situated within North-Central Nigeria, soil erosion has emerged as a critical threat to agricultural productivity, environmental sustainability, and rural livelihoods. This has resulted to the poor environmental scenario of the state (Oladimeji et al., 2020). The state's economy also relies heavily on farming; however, widespread land degradation continuously impairs soil fertility and degrades arable land. This vulnerability is driven by a complex interplay of natural and anthropogenic factors, including extensive land clearance, unsustainable tillage, deforestation, and overgrazing (Ejaz et al., 2023). Chief among these triggers, however, are climatic and morphological factors - specifically rainfall erosivity and topographic relief. High-intensity seasonal precipitation delivers immense kinetic energy to exposed topsoils, while steep slopes and undulating terrain accelerate surface runoff velocity, intensifying sheet, rill, and gully erosion across the region.

To address these challenges, this study utilized rainfall erosivity as a key climatic input to systematically map and quantify the spatial extent of rainfall-induced soil detachment and continuous sediment transport across Kwara State. By coupling spatially distributed rainfall

erosivity modeling with terrain attributes within a Geographic Information System (GIS) environment, this research elucidates the spatial heterogeneity of soil loss mechanisms across the state's major catchments. The resulting spatial assessments provide an empirical foundation for identifying critical erosion hotspots, predicting downstream sediment delivery dynamics, and guiding targeted land-use planning and watershed conservation interventions.

Study Area: Kwara State, Nigeria

Kwara State is located in north-central Nigeria (Fig 1), within the Guinea savanna ecological zone. It lies between latitudes 8°00′N and 10°00′N and longitudes 2°30′E and 6°30′E, covering an area of approximately 36,825 km². The state is made up 16 tocal government areas with the capital Ilorin (table 1), and it shares boundaries with Niger State to the north, Kogi State to the east, Oyo, Osun, and Ekiti States to the south, and the Republic of Benin to the west.

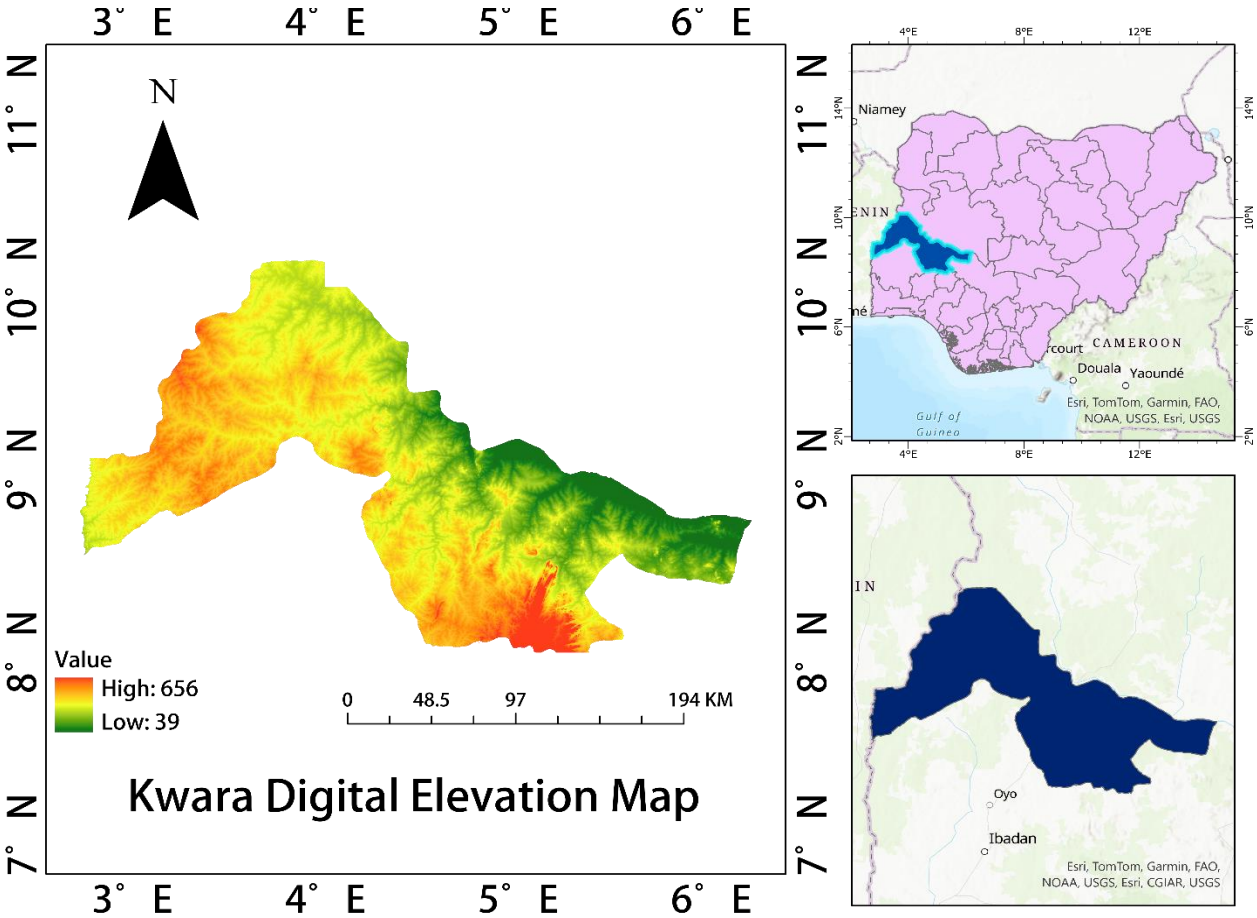


Fig. 1. *Map of Kwara State showing the Digital Elevation Map*

Kwara State experiences a tropical climate characterized by distinct wet and dry seasons. The rainy season typically lasts from April to October, with mean annual rainfall ranging between 1,200 mm and 1,500 mm, while the dry season spans November to March under the influence of the northeast trade winds (Harmattan). Temperatures generally range from 25°C to 35°C throughout the year. The natural vegetation is predominantly Guinea savanna, consisting of

tall grasses interspersed with scattered trees, although much of the original cover has been modified by agricultural activities and settlement expansion (Adeleke, 2024).

The state is underlain mainly by Basement Complex rocks, which have weathered to form shallow to moderately deep soils (Adebiyi et al., 2022). Common soil types include Ferric Luvisols, Alfisols, and some sandy loams, particularly in areas with steeper slopes (Fig 1) and intensive cultivation (Alabi et al., 2024). These soils are generally coarse-textured with low to moderate clay content, making them susceptible to erosion, especially where vegetation cover is sparse or land use is intensive.

Agriculture is the dominant land use in Kwara State, with crops such as maize, cassava, yam, millet, and sorghum widely cultivated. Rapid population growth, urbanization, and expansion of farmland have increased pressure on the land, leading to deforestation, overgrazing, and loss of vegetative cover. These factors, combined with variable rainfall intensity and undulating topography in some areas, have contributed to significant soil erosion problems, including sheet, rill, and gully erosion, particularly in Ilorin and surrounding local government areas.

Recent studies using the Revised Universal Soil Loss Equation (RUSLE) integrated with GIS and remote sensing indicate that approximately 3.81% of Kwara State falls within the high erosion risk class, with higher susceptibility in areas with steep slopes, sparse vegetation, and intensive land use. About 23.04% is classified as medium risk, while 73.15% is low risk, providing a regional baseline for prioritizing soil conservation interventions (Musa et al., 2021; Alabi et al., 2024).

Table 1. *Local Government Areas of Kwara State and their Geographic Description*

S/N	LGA Name	Longitude	Latitude	Area (km²)
1	Asa	4.5371	8.2335	1,286
2	Baruten	3.2436	9.134	9,749
3	Edu	4.9799	8.935	2,542
4	Ekiti	5.1988	8.2236	480
5	Ifelodun	4.8655	8.5768	3,435
6	Ilorin East	4.5819	8.8455	486
7	Ilorin South	4.4626	8.6465	174
8	Ilorin West	4.4625	8.4773	105
9	Irepodun	4.8655	8.5768	737
10	Isin	4.9799	8.338	633
11	Kaiama	4.159	9.4922	6,971
12	Moro	4.2536	8.8007	3,272
13	Offa	4.8257	8.348	95
14	Oke Ero	5.3431	8.4027	438
15	Oyun	4.7809	8.144	476
16	Patigi	5.552	8.633	2,913

Materials and Methods

Data Acquisition

The primary dataset utilized for quantifying rainfall erosivity (R-factor) and assessing long-term soil loss dynamics comprises continuous precipitation records spanning an 11-year observation period from 2020 to 2025 obtained from the data base of Nigeria meteorological agency (MIMET) which is as a control and from 8 different rain gauges scattered across the state (table. 2). To systematically capture temporal variability, evaluate medium-term climatic trends, and minimize localized annual precipitation anomalies, the analysis was structured into six periods a five-year interval framework.

Table 2. *Location of Rain gauges*

Station	Long	Lat
S1	5.223	8.097
S2	4.681	8.176
S3	4.498	8.566
S4	5.998	8.528
S5	5.382	8.91
S6	4.669	9.032
S7	4.181	9.443
S8	3.773	9.903
S9	3.102	8.989

Rainfall Erosivity Estimation

The classic method for computing storm rainfall erosivity was developed by **Wischmeier and Smith (1958, 1978)**. The storm erosivity index (EI_{30}) is defined as the product of the total kinetic energy (E) of a rainfall event and its maximum continuous 30-minute intensity (I_{30}) equation 1:

$$EI_{30} = E \times I_{30} \quad (1)$$

Where:

- E= total storm kinetic energy (MJ · ha^{-1})
- I_{30}= peak 30-minute rainfall intensity (mm · h^{-1})

The **annual rainfall erosivity factor (R)** for a location is calculated as the long-term average of summed EI_{30}values across all erosive storms in a year as expressed in equation 2:

$$R = \frac{1}{N}\sum_{j=1}^{N}\left[\sum_{k=1}^{m}(EI_{30})_k\right] \quad (2)$$

Where:

- N= number of recorded years
- m= number of erosive events in year j

Storm Kinetic Energy

Total storm kinetic energy (E) is derived by integrating unit kinetic energy (e_r) over rainfall increments (P_r) equation 3:

$$E = \sum_{r=1}^{k} e_r \cdot P_r \quad (3)$$

In RUSLE **(Renard et al., 1997)**, unit kinetic energy is estimated using equation 4:

$$e_r = 0.29[1 - 0.72\exp(-0.05 \cdot i_r)] \quad (4)$$

Where $i_r$is rainfall intensity (mm $\cdot$ h^{-1}). This accounts for the physical limit of raindrop size: at very high intensities ($i_r > 75$), raindrops break apart, causing kinetic energy to plateau. However, high-resolution pluviograph data (5–30 min intervals) are often unavailable in A Modified Fournier Index (MFI) Arnoldus (1980) proposed the MFI to capture rainfall

$$\text{MFI} = \sum_{m=1}^{12} \frac{p_m^2}{P}$$

A Modified Fournier Index (MFI) Arnoldus

$$\text{MFI} = \sum_{m=1}^{12} \frac{p_m^2}{P} \quad (5)$$

Where p_m= mean monthly rainfall (mm), P= mean annual rainfall (mm). High MFI values indicate strong seasonality and concentrated rainfall.

This study uses derived the rainfall erosivity for this research using the equation formulated by Arnoldus (1980). it given as in equation 6

$$R = 0.264 \times (MFI)^{1.50} \quad (6)$$

Results

Figure 2 shows the rainfall distribution in Kwara State, which was analyzed for six epochs: 2000, 2005, 2010, 2015, 2020 and 2025. The rainfall was classified into five classes: Very Low, Low, Moderate, High and Very High and All six maps exhibited a distinct northwest to southeast rainfall gradient, which remained consistent throughout the study period.

The Very Low and Low Rainfall Zones which is red and orange in colour are zones dominated the northern and northwestern parts of the state, covering LGAs such as Baruten, Kaiama, Edu and Patigi. This zone corresponds to the Guinea Savanna agro-ecological zone characterized by lower annual rainfall and prolonged dry season. The moderate Rainfall Zone,

yellow in colour. This zone occupied the central part of the state, including Moro, Ilorin East, Ilorin West and parts of Ifelodun. It served as a transitional belt between the dry north and the wet south.

Finally, the high and Very High Rainfall Zones which are in dicated by the Light Green and Dark Green and are concentrated in the southern and southeastern parts of the state, comprising Ekiti, Oke-Ero, Isin, Irepodun, Offa, Oyun and Ifelodun LGAs. The persistent high rainfall in this corridor is attributed to its location in the derived savanna and proximity to the humid forest zone.

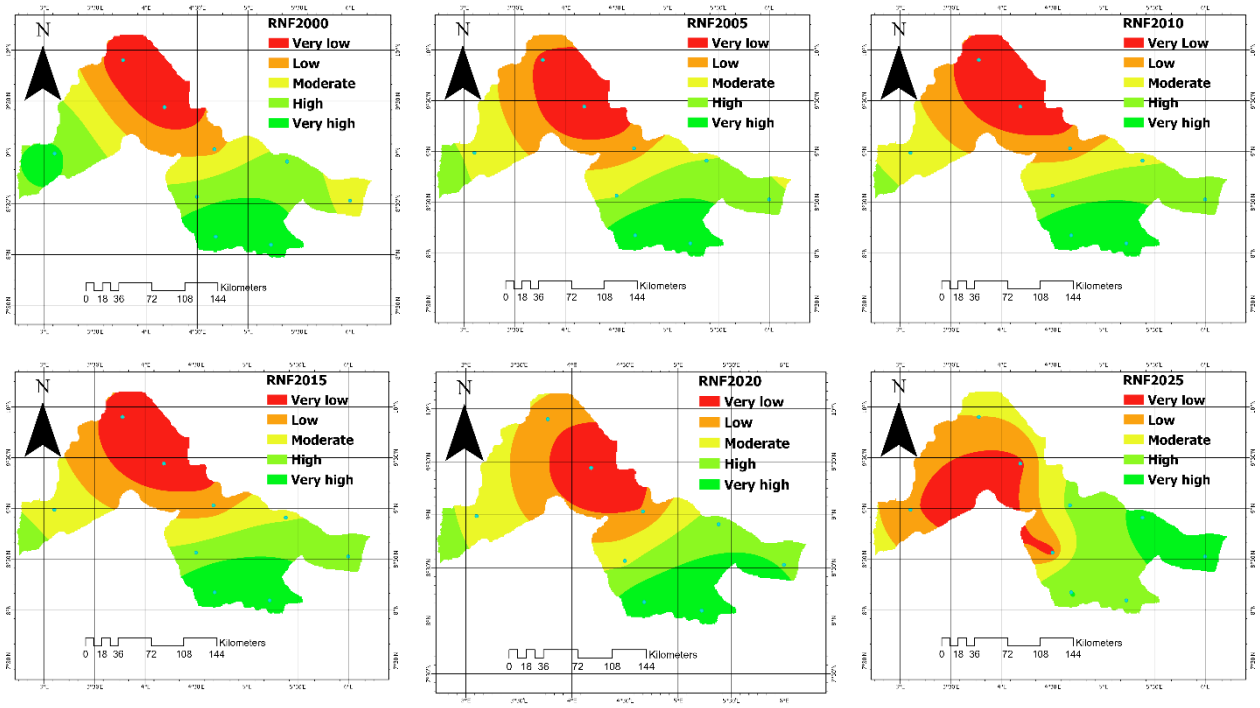


Fig. 2. *Spatial Variation of Rainfall from 2020 to 2025*

Figure 3 shows Erosivity (R-Factor) maps for Kwara State, 2000-2025. In RUSLE, R-Factor measures the power of rainfall to cause soil erosion. Higher value means more erosive rain. The pattern has 6-time steps: In 2000 the values ranged from a Low of 566.32 to a High of 749.05. In 2005 it ranged from 601.5 to 923.28. In 2010 it ranged from 777.17 to 1277.3. In 2015 it ranged from 593.28 to 872.2. In 2020 it ranged from 777.5 to 1054.9. And in 2025 it ranged from 693.7 to 893.7. All in MJ mm ha^{-1} h^{-1} yr^{-1}.

The pattern is the same in all 6 years. It increases from the northwest to the southeast. In the west and northwest, which is Baruten, Kaiama and parts of Patigi, the values are lowest. With yellow to orange colour. This is because this area receives less rainfall and less intense rainfall. In the south and southeast, which is Ekiti, Oke-Ero, Isin, Ifelodun, Offa and Irepodun axis, the values are highest. The color there is dark purple to black. This area receives higher and more intense rainfall, so the erosive power is highest. The central part of the state is the transition

zone. It shows moderate erosivity. This pattern directly matches your RNF maps. Where rainfall is Very High in the south, erosivity is also Very High.

From 2000 to 2010, there was a sharp increase in erosivity. In 2000, the lowest value was 566.32 and the highest was 749.05. By 2010, the lowest had risen to 777.17 and the highest to 1277.3. 2010 is the most erosive year in the entire series. The dark purple high-risk area is also largest in 2010. In 2015, there was a drop. The values fell back to a Low of 593.28 and a High of 872.2, which is close to the 2000 and 2005 levels. This suggests that 2015 was a year with less intense rainfall.

In 2020, there was a second peak. The High value rose again to 1054.9 and the Low to 777.5. The high-risk purple area expanded again to cover almost all of southern Kwara. In 2025, there is a slight decline from 2020, with a High of 893.7 and a Low of 693.7. But even though it is lower than 2020, the Low value in 2025 is still much higher than the entire range in 2000. This means that even the least erosive part of Kwara in 2025 is now more erosive than the most erosive part was in 2000. Overall, Kwara is becoming more erosive. The background Low value is rising steadily, which means rainfall is becoming more intense, not just more in total amount.

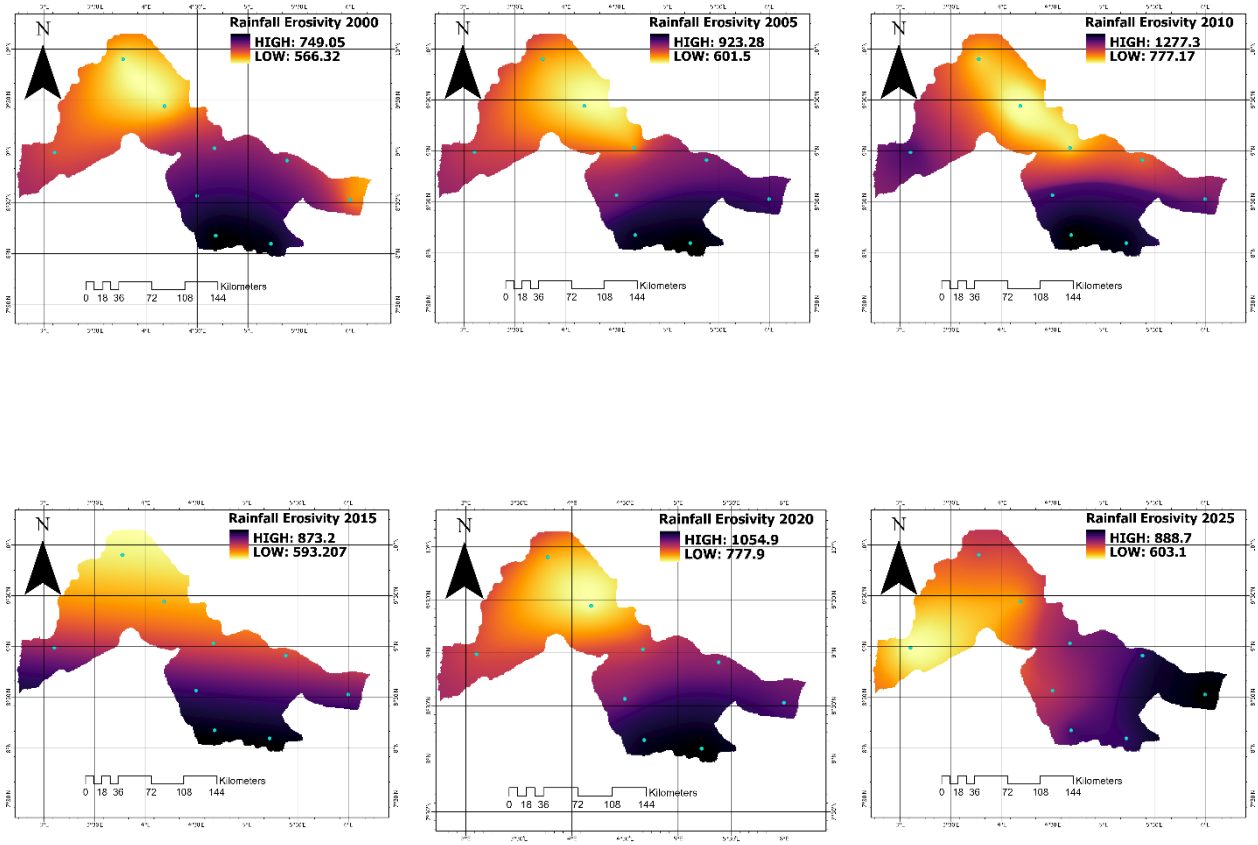


Fig. 3. *Spatial Variation of Rainfall erosivity from 2020 to 2025*

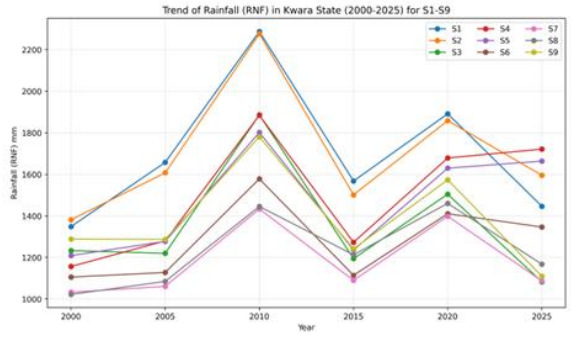
Table 3. *Rainfall Data for the Selected Stations*

Station	RNF2000	RNF2005	RNF2010	RNF2015	RNF2020	RNF2025
S1	1048.92	1357.76	1987.69	1268.14	1591.63	1146.63
S2	1081.4	1307.91	1976.62	1201.45	1558.75	1295.94
S3	933.07	920.14	1586.79	894.54	1204.81	782.88
S4	856.83	979.97	1584.69	973.01	1378.92	1421.75
S5	909	977.84	1501.82	936.14	1329.96	1363.94
S6	805.82	827.79	1278.54	814.15	1110.77	1046.63
S7	733.02	760.98	1133.79	790.04	1098.67	787.63
S8	722.16	784.91	1145.66	912.91	1160.57	867.81
S9	988.77	987.56	1480.55	941.8	1273.91	809.88

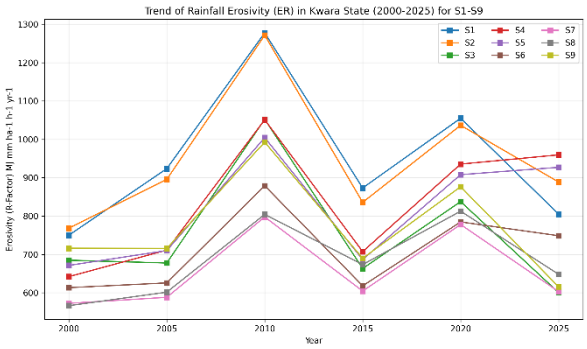
Table 4.*Rainfall Erosivity Calculated for the selected Stations*

Station	Long	Lat	ER2000	ER2005	ER2010	ER2015	ER2020	ER2025
S1	5.223	8.097	749.973	923.5411	1277.562	873.1747	1054.976	804.8861
S2	4.681	8.176	768.2268	895.5254	1271.34	835.6949	1036.498	888.7983
S3	4.498	8.566	684.8653	677.5987	1052.256	663.2115	837.5832	600.4586
S4	5.998	8.528	642.0185	711.2231	1051.076	707.3116	935.433	959.5035
S5	5.382	8.91	671.338	710.0261	1004.503	686.5907	907.9175	927.0143
S6	4.669	9.032	613.3508	625.698	879.0195	618.0323	784.7327	748.6861
S7	4.181	9.443	572.4372	588.1508	797.67	604.4825	777.9325	603.1281
S8	3.773	9.903	566.3339	601.5994	804.3409	673.5354	812.7203	648.1892
S9	3.102	8.989	716.1687	715.4887	992.5491	689.7716	876.4174	615.6326

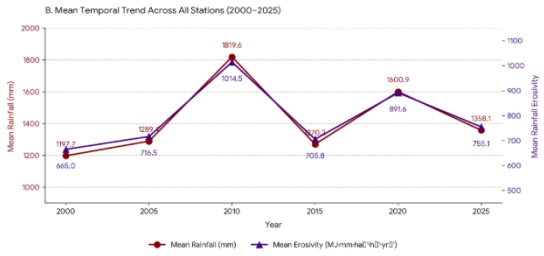
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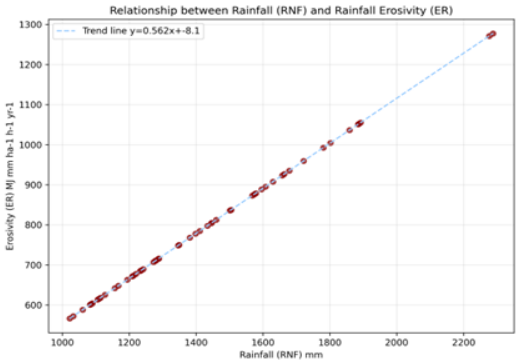


Fig. 4. *Trend of RNF in Kwara State (2000-2025) for sample points S1-S9*

Fig. 5. *Trend of Rainfall Erosivity in Kwara State (2000-2025) for sample points S1-S9*

Fig. 6. *Combined Average Trend of RNF and Rainfall Erosivity (ER) in Kwara State (2000-2025)*

Fig. 7. *Relationship between Rainfall (RNF) and Rainfall Erosivity (ER)*

Table 3 - 4 and figure 4-7 shows the temporal trend and graphical representation of the rainfall and erosivity respectively in the six locations where the rain gauges are mounted.

Figure 4 shows temporal variation of rainfall for nine sample points (S1-S9) across Kwara State between 2000 and 2025. The figure reveals a consistent temporal pattern across all sample points. Rainfall increased from 2000 to a peak in 2010, with 2010 recording the highest rainfall for all points. For instance, S1 increased from 1348.92 mm in 2000 to 2287.69 mm in 2010. A sharp decline was observed in 2015, followed by a second increase in 2020, and a moderate decline in 2025. Spatially, S1 and S2 consistently recorded the highest rainfall values, indicating that the southern part of the state is the wettest, while S7 and S8 recorded the lowest values, confirming that the northern part is the driest. The average rainfall for the state rose from 1197.66 mm in 2000 to 1819.57 mm in 2010 and stood at 1358.12 mm in 2025.

Figure 5 shows temporal variation of rainfall erosivity (R-Factor) for nine sample points (S1-S9) across Kwara State between 2000 and 2025. The trend of rainfall erosivity mirrors exactly the trend of rainfall. Erosivity increased from 2000 to a peak in 2010, declined in 2015, increased again in 2020, and declined slightly in 2025. The year 2010 recorded the highest erosivity for all points, with S1 reaching 1277.56 MJ mm ha-1 h-1 yr-1. The lowest erosivity was recorded in 2000, with S8 at 566.33 MJ mm ha-1 h^{-1} yr^{-1}. Similar to rainfall, S1 and S2 in the south are the most erosive while S7 and S8 in the north are the least erosive. The state average erosivity increased from 664.96 MJ mm ha-1 h^{-1} yr^{-1} in 2000 to 1014.47 MJ mm ha-1 h^{-1} yr^{-1} in 2010 and was 755.14 MJ mm ha-1 h^{-1} yr^{-1} in 2025. This shows that the erosive power of rainfall in Kwara has increased over the last 25 years.

Figure 6 shows combined average trend of rainfall and rainfall erosivity in Kwara State between 2000 and 2025. The combined average trend confirms that rainfall and erosivity move together in the same direction. Both parameters peaked in 2010 with an average rainfall of 1819.57 mm and average erosivity of 1014.47 MJ mm ha-1 h^{-1} yr^{-1}, and both recorded their lowest values in 2000. The parallel movement of both lines from 2000 to 2025 validates that rainfall variability directly controls erosivity variability in Kwara State. The fact that the 2025 average erosivity of 755.14 MJ mm ha-1 h^{-1} yr^{-1} is higher than the 2000 average of 664.96 MJ mm ha-1 h^{-1} yr^{-1}, despite similar rainfall levels, indicates that rainfall is becoming more intense and more erosive over time, not just more in amount.

Figure 7 shows the scatter plot and linear regression between rainfall and rainfall erosivity for all sample points and years in Kwara State. The figure shows a perfect positive linear relationship between rainfall and rainfall erosivity. The regression equation is $ER = 0.562RNF - 8.1$, with an R-squared value of approximately 1.0. This implies that for every 1 mm increase in rainfall, erosivity increases by 0.562 units. This strong correlation proves that rainfall amount is the primary determinant of soil erosion risk in the study area. Where rainfall is high, erosivity is also high, and vice versa.

Discussion

The persistent NW-SE rainfall gradient observed in this study corroborates the established climatology of Kwara State and Nigeria as a whole, where rainfall decreases with increasing latitude which is similar to the work of Adeleke (2024). This is controlled by the northward and southward migration of the Inter-Tropical Discontinuity (ITD).

The temporal variability from 2000 to 2025 is indicative of climate variability in the North-Central region. The fluctuation between expansion (2000, 2010, 2020) and contraction (2005, 2025) of the Very Low zone reflects the 5–10-year quasi-cyclic pattern of rainfall anomalies reported in the Guinea Savanna. The RNF 2020 pattern, characterized by a concentrated circular dry core, suggests a shift from widespread low rainfall to localized intense drought, which is more damaging to rain-fed agriculture. Conversely, RNF 2025, which shows the smallest dry zone and an expanded wet zone, suggests a recent wetting trend. However, this

wetting does not necessarily translate to lower erosion risk, as high total rainfall often comes with high-intensity storms (Adeleke, 2024; Ahmed, 2025).

The implication of the pattern of rainfall is that the northern LGAs (Baruten, Kaiama, Edu, Patigi) are consistently rainfall-stressed and remain vulnerable to drought, late onset of rains, and crop failure, requiring drought-tolerant crops and irrigation. The southern LGAs (Ekiti, Oke-Ero, Isin, Offa) have more reliable rainfall for water-demanding crops like yam, cassava and rice, but face higher risks of flooding, leaching, and soil erosion due to sustained high rainfall.

The direct spatial correspondence between RNF and R-Factor confirms that rainfall amount and intensity are the primary drivers of erosivity in the study area this is similar to the work of Ahaneku et al., (2017). Where RNF was Very High, R-Factor was also High. This is expected as the R-factor in RUSLE is derived from rainfall amount and intensity. The temporal increase in R-factor from 2000 to 2025, despite fluctuating RNF extent, suggests that rainfall in Kwara is not only variable but becoming more intense and erosive. The sharp peaks in 2010 and 2020 correspond to years of reported intense rainfall events and flooding in North-Central Nigeria. The decline in 2015 may be linked to a relatively less intense rainfall year. The 2025 scenario, where rainfall extent increases but R-factor remains high, implies a change towards more widespread but still highly erosive rainfall.

The southern LGAs - Ekiti, Oke-Ero, Isin, Ifelodun, Irepodun, Offa - remain the most vulnerable to water erosion. The high R-values (>1000) in these areas, combined with undulating topography and farming activities that leave soil bare at the onset of rains, creates a high risk for sheet, rill and gully erosion. The northern LGAs, while currently lower risk, show an increasing baseline erosivity, meaning soil conservation measures cannot be limited to the south alone.

Finally, the study reveals that while the spatial pattern of rainfall in Kwara is stable, its erosive power is increasing, with southern Kwara emerging as a critical soil erosion hotspot that requires urgent conservation planning.

Conclusion

This study assessed the spatio-temporal distribution of rainfall and rainfall erosivity in Kwara State for the period 2000 to 2025 using geospatial techniques and sample points S1 to S9 which are points where mounted rain gauges acessed.

The research concludes that rainfall pattern in Kwara State is spatially predictable but temporally unstable. While the north-south gradient has remained stable over 25 years, the magnitude and erosive power of rainfall have increased. The southern LGAs are the most vulnerable to soil erosion due to the double impact of high rainfall amount and high erosivity. The year 2010 remains the most critical erosion year in the last 25 years, followed by 2020. The northern LGAs, though currently less erosive, show a rising trend in erosivity and can no longer be considered safe from water erosion.

The Kwara State Ministry of Environment and relevant agencies should prioritize southern LGAs, particularly Ekiti, Oke-Ero, Isin, Ifelodun and Offa, for immediate soil conservation interventions. Measures such as contour ploughing, terracing, cover cropping,

agroforestry and construction of check dams should be implemented to reduce soil loss and Future studies should integrate other RUSLE factors such as soil erodibility, slope length and steepness, vegetation cover and conservation practice to model actual soil loss in tonnes per hectare per year for Kwara State. Higher temporal resolution data such as daily rainfall should also be used to capture storm-level intensity.

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