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Article

Soil Erosion Risk Assessment Using Remote Sensing and GIS: An Integrated RUSLE-Frequency Approach

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Abstract: Soil erosion is a major environmental challenge in tropical regions due to the interaction of intense rainfall, fragile soils, and unsustainable land use. This study assessed soil erosion risk in Agulu-Nanka, southeastern Nigeria, using an integrated GIS, remote sensing, Revised Universal Soil Loss Equation, and Frequency Ratio modeling approach to identify erosion hotspots and validate erosion susceptibility factors. It addresses the lack of localized, high-resolution soil erosion mapping and model validation using observed field erosion features in the study area despite existing regional erosion studies in Anambra State. Multi-source datasets were used to derive Revised Universal Soil Loss Equation factors and produce high-resolution erosion risk maps, which were validated using gully occurrence data. Results indicate extremely high rainfall erosivity (mean R = 110,562.09 MJ-MM/ha-hr-yr) and moderately to highly erodible soils (mean K = 1.39) as key erosion drivers. Steep slopes (LS > 4.00) more than doubled gully occurrence likelihood (FR = 2.21), while poorly vegetated and unmanaged areas recorded high susceptibility (FR > 2.0). Estimated soil loss reached 86.34 t/ha/yr, with high and very high-risk zones covering less than 4% of the area but posing significant threats to land productivity and infrastructure. The study confirms the multi-factorial nature of erosion in Agulu-Nanka and demonstrates the effectiveness of the RUSLE-FR framework for hotspot identification and evidence-based land use planning.

Keywords: Risk Assessment; Soil Erosion; Remote Sensing and GIS; Agulu-Nanka; RUSLE.

1. Introduction

The most widely held view of the soil, however, is as a medium for plant growth and the provision of food and fibre directly or through the immediate stage of animals [1]. Soil erosion is a complex geomorphological process involving the detachment, transport, and deposition of soil particles by erosive agents such as water and wind. It stands as a pervasive global environmental issue, threatening agricultural productivity, land degradation, biodiversity, and water quality [2], [3]. Soil erosion is a critical environmental concern that undermines agricultural productivity, threatens food security, and contributes to ecological degradation across the globe [4], [5]. It results from a combination of natural drivers such as high-intensity rainfall, slope dynamics, and soil properties and human-induced pressures including deforestation, overgrazing, poor farming practices, and unplanned urban expansion [6], [7]. Therefore, accurate monitoring, assessment, and prediction of soil erosion risk are paramount for effective land management, conservation planning, and ensuring future food security.

The impacts of soil erosion are particularly severe in developing regions, where loss of fertile topsoil, gully formation, and sedimentation of water bodies have far-reaching consequences for livelihoods, biodiversity, and ecosystem services [8], [9]. Aggravated soil erosion poses a critical environmental challenge in many parts of southeastern Nigeria, including Aguata in Anambra State. This region's tropical climate marked by high-intensity rains and its undulating terrain with soils susceptible to erosion have led to increased land degradation and sedimentation in river systems [8], [10]. Many erosion-prone communities rely on fragmented or outdated soil conservation strategies that are not informed by geospatial evidence or spatially explicit risk models [11]. The Revised Universal Soil Loss Equation (RUSLE), when integrated with GIS and remote sensing, has emerged as a widely accepted framework for mapping soil loss and erosion risk [8], [12]-[15].

Recent studies in Anambra have applied the RUSLE-GIS-Remote Sensing methodology to neighboring watersheds, such as the Obibia River, quantifying erosion risk and demonstrating that most erosion occurs in undulating landscapes near river bodies [8]. Similarly, [11] found that, across Anambra's mosaic of land uses, between 20% and 60% of the catchment area falls into moderate-to-extreme erosion classes, highlighting urgent land management needs. These findings are consistent with broader regional analyses, such as those in Imo River Basin and Nasarawa State, which used DEM-derived morphometric and RUSLE parameters to classify watershed erosion susceptibility with over 80% prediction accuracy [16], [17].

Despite this growing body of work, none has focused on using RUSLE for Agulu-Nanka specifically, an area characterized by highly erodible tropical soils, mixed agricultural land uses, and parts of the State's key drainage system the Omambala River network [10]. Given its distinct topography and land-cover dynamics, localised erosion mapping is essential. Moreover, remote sensing and GIS technologies have yet to be calibrated against observed erosion features in Anambra, such as rill formation, gully development, and sediment deposition along farm margins, a gap that this research aims to address. By applying a multi-criteria RUSLE approach (incorporating rainfall erosivity, soil erodibility, slope factors, vegetation cover, and conservation practices) to Agulu-Nanka, this study seeks to produce a high-resolution soil erosion-risk map. It also validated model outputs through limited field surveys and morphological observations. This would not only fill a critical spatial data gap but also generate evidence-based insights for sustainable land-use planning and erosion mitigation specific to Agulu-Nanka environmental context.

This paper is organized as follows: Section one presents the overall background to the study. Section two has to do with the materials and methods used. Section three is the results and discussions of the analyzed data. Section fours presents the conclusion and recommendations of the study.

2. Materials and Methods

2.1. The study area

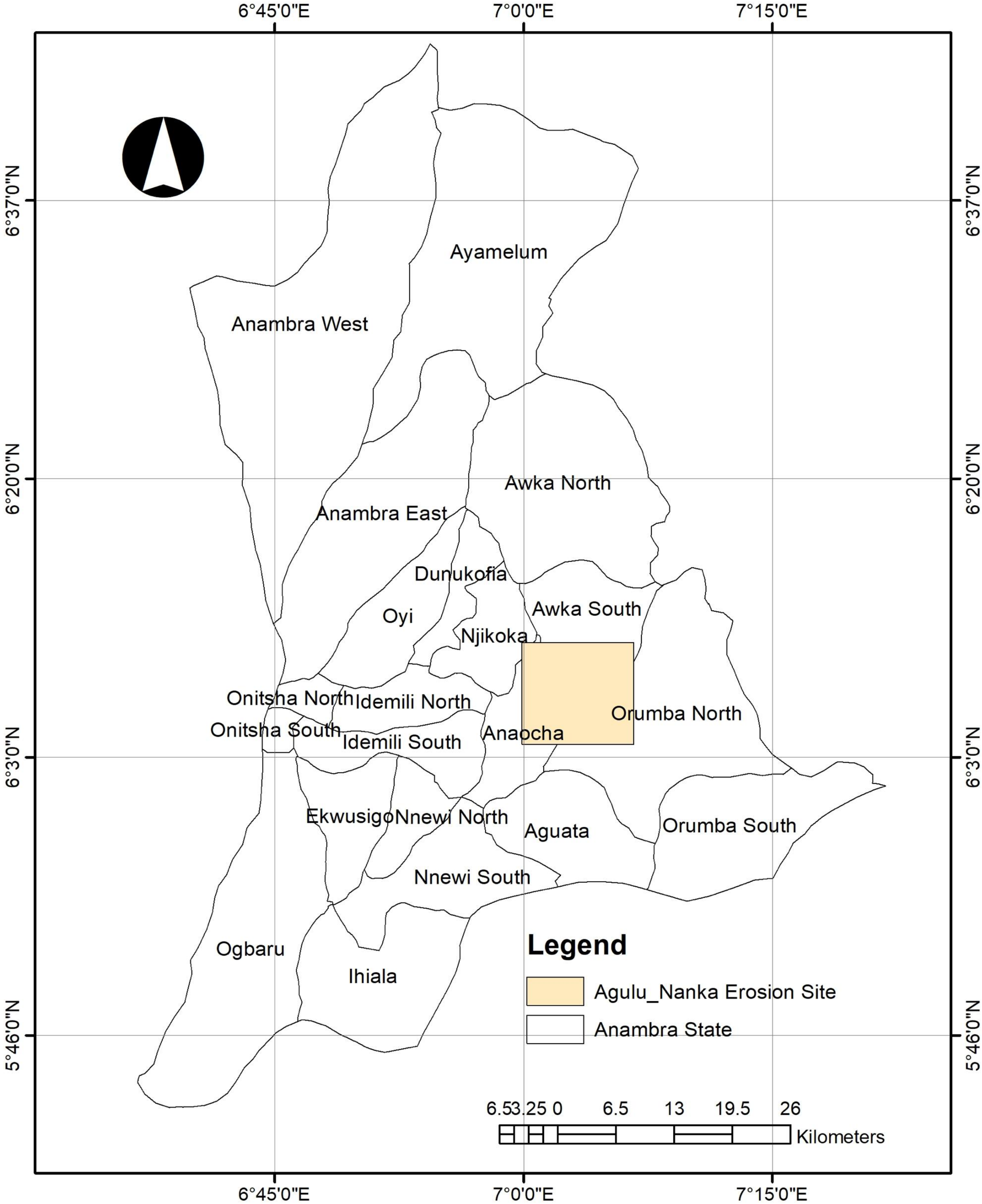
Geographically, the Agulu-Nanka erosion site is situated between latitudes 6°05'N and 6°09'N, and longitudes 7°05'E and 7°10'E (Figure 1 and 2). It is approximately 25 kilometers southeast of Awka, the capital city of Anambra State. The area is well-connected by road networks linking it to other major urban centres, including Onitsha, Enugu, and Nnewi. The towns within this region are semi-urban and predominantly agrarian, with a mixture of rural settlements and expanding residential layouts.

The topographic configuration of the Agulu-Nanka landscape is marked by undulating terrain and deeply incised valleys, shaped predominantly by intensive water erosion. Elevations range from approximately 100 to 300 meters above sea level. The landscape in the area consists of highlands and valleys produced as a result of neotectonic uplift and erosion [18]. The study area is geologically underlain by the Nanka Sands, a member of the Ameki Formation, which forms part of the Tertiary sedimentary sequence of the Anambra Basin. These sands are friable, loosely consolidated, and highly porous, making them extremely susceptible to detachment under erosive forces.

The Agulu-Nanka erosion site experiences a tropical humid climate with distinct wet and dry seasons. The rainy season typically extends from April to October [19], with peak rainfall observed between July and September. Annual rainfall averages between 1,800 mm and 2,200 mm, delivered primarily through high-intensity convective storms. Temperatures range between 25°C and 32°C throughout the year, with high relative humidity often exceeding 80% during the wet season. The erosivity of rainfall is exacerbated by short-duration, high-intensity events that generate significant kinetic energy upon impact with the soil surface. Gully erosion poses a severe and persistent environmental threat in the Agulu-Nanka region. The area is home to some of the deepest and most rapidly expanding gullies in Nigeria, with widths exceeding 20 meters and depths reaching over 30 meters in certain locations. These gullies frequently disrupt transportation infrastructure, displace communities, destroy farmlands, and degrade the ecological integrity of the landscape.

2.2. Methods

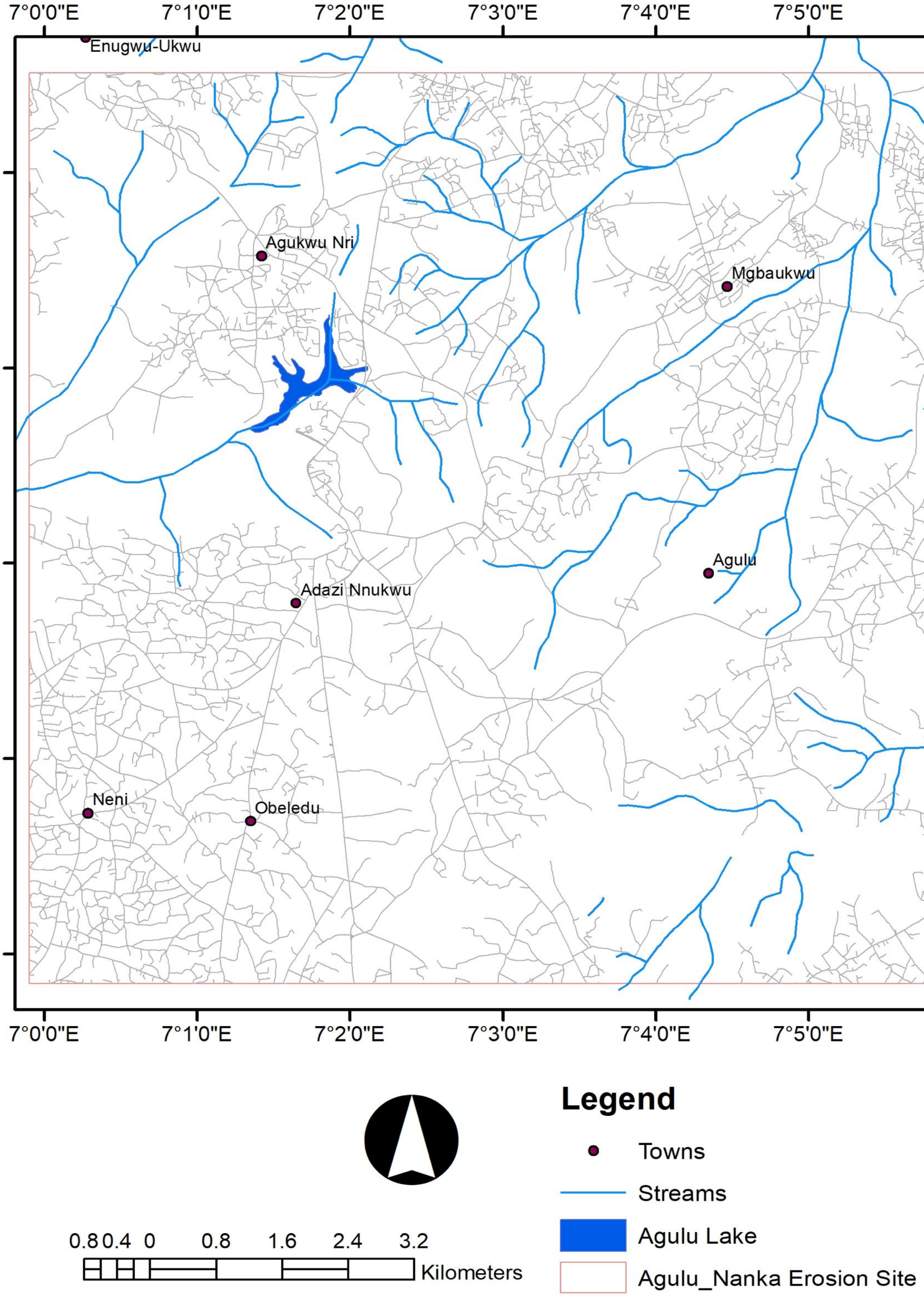
This study adopted an integrated geospatial approach combining Geographic Information Systems (GIS), remote sensing, and spatial statistical modeling to assess soil erosion risk in Agulu-Nanka and its environs. Remotely sensed imagery was sourced from USGS Earth Explorer (Landsat 8 OLI imagery) which provides a longer historical archive with moderate spatial resolution (30 m). Multi-source primary and secondary datasets including SRTM DEM, CHIRPS rainfall data, Harmonized World Soil Database, and Landsat 8 OLI imagery were acquired, preprocessed, and standardized to a common spatial resolution and coordinate system (See Figure 3). The Revised Universal Soil Loss Equation (RUSLE) served as the core analytical framework, with its five factors (R, K, LS, C, and P) derived using established empirical models and GIS-based terrain and land cover analyses. Raster-based map algebra was applied in ArcGIS to estimate average annual soil loss and generate erosion risk maps classified into susceptibility zones. In addition, a Frequency Ratio (FR)



Source: Department of Surveying and Geoinformatics Unizik, 2025

Figure 1. Map of Anambra State showing the study area.

model was employed to statistically evaluate the spatial relationship between observed gully occurrences and erosion-controlling factors, thereby validating model outputs. The methodology provides a robust, spatially explicit basis for identifying erosion-prone areas and supporting evidence-based land management and conservation planning.



Source: Department of Surveying and Geoinformatics Unizik, 2025

Figure 2. Map of the Study Area.

The Rainfall Erosivity Factor (R) quantifies the impact of raindrop intensity and frequency on soil particles and is a major driver of detachment processes. The R-factor was derived from long-term rainfall data sourced from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) repository. The interpolated rainfall surface was generated using Inverse Distance Weighting (IDW) in ArcGIS, ensuring spatial continuity across the study area. Due to the unavailability of site-specific rainfall intensity data, a regionally calibrated empirical model ($R = 38.5 \times P - 1571$), where P represents mean annual precipitation in millimeters, was applied to estimate the erosivity index. The generated R-factor raster was resampled to a 30-metre resolution to match the spatial scale of other input datasets.

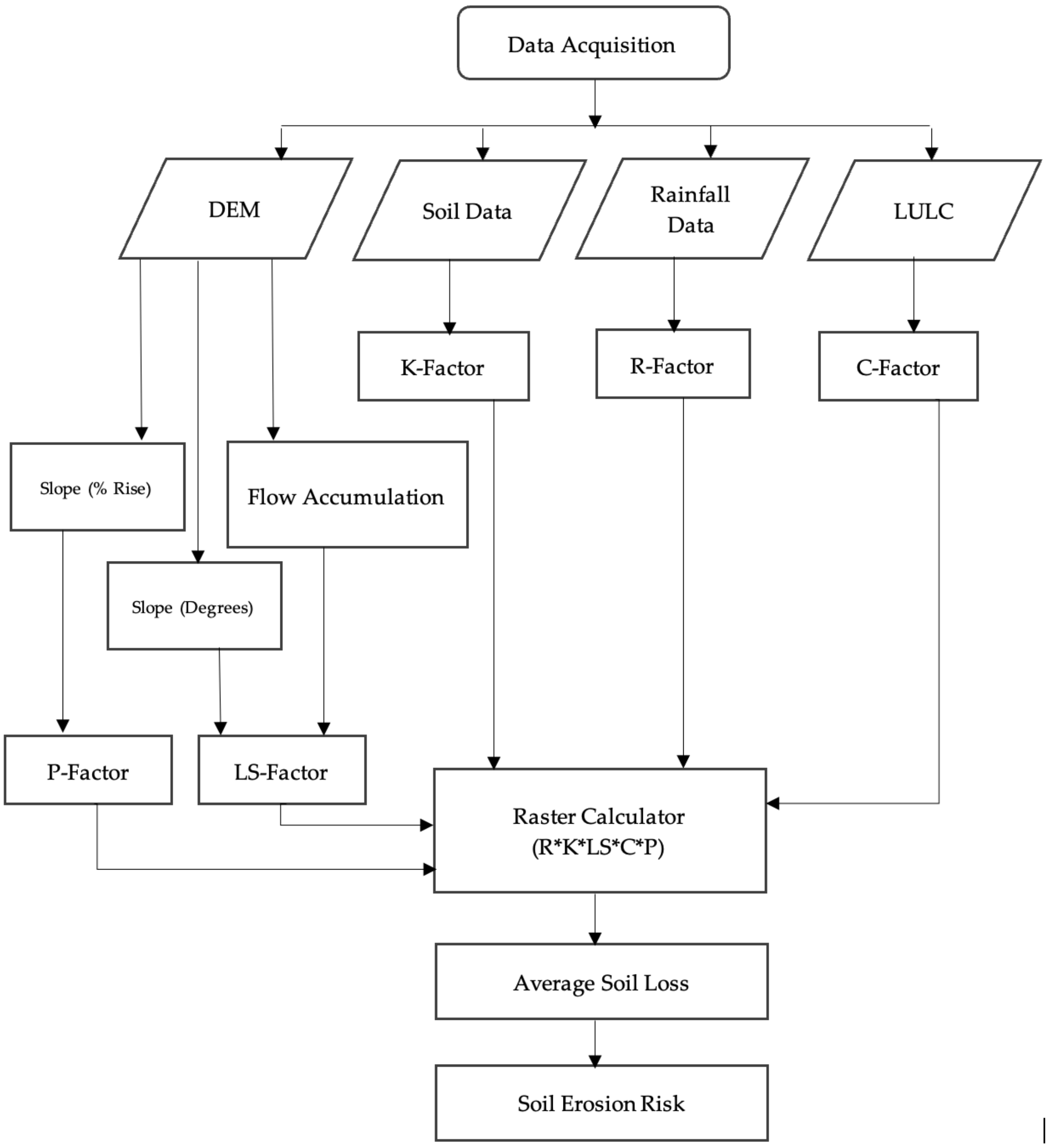


Figure 3. Flowchart for the study.

The Soil Erodibility Factor (K) measures the inherent susceptibility of soil types to detachment and transport under the influence of rainfall and surface runoff. Soil samples and attribute data comprising particle size distribution (percentages of sand, silt, and clay), organic matter content, soil structure, and permeability class were obtained from national soil databases and previous surveys.

These attributes were inputted into Equation 1 to compute the K values for each soil unit.

$$K = \frac{2.1 \times 10^{-4}(12 - OM) \times M^{1.14} + 3.25(S_{str} - 2) + 2.5(P - 3)}{100} \quad (1)$$

Where:

- M = (% silt + % very fine sand) × (100 - % clay)
- OM = Organic matter content (%)
- S_{str} = Soil structure code (1–4)
- P = Profile permeability class (1–6)

The resulting K-value was georeferenced and converted into a raster format, facilitating integration with other RUSLE parameters.

The Topographic Factor (LS) reflects the influence of slope gradient and slope length on the acceleration of surface runoff and soil particle detachment. This parameter was computed from a 30 m resolution Digital Elevation Model (DEM) Equation 2, which is particularly suitable for raster-based environments. The equation integrates flow accumulation and slope angle, derived respectively from the Flow Accumulation and Slope functions in ArcGIS Spatial Analyst toolbox. The LS-factor raster thus produced encapsulates the geomorphological characteristics influencing water-induced erosion.

$$LS = \left(\frac{Flow\ accumulation \times Cell\ Size}{22.13}\right)^{0.4} \times \left(\frac{\sin \sin(slop(in\ radians))}{0.0896}\right)^{1.3} \quad (2)$$

The independent variables comprised the five physical parameters previously modelled for the RUSLE application: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and support practice (P). Each of these factors was reclassified into discrete ordinal classes (five) based on natural breaks to facilitate statistical comparison. For example, the LS-factor was classified into classes such as 0–5, 5–15, 15–30, 30–45, and >45 degrees of slope to reflect different degrees of terrain steepness and length.

The frequency ratio (FR) for each class within a given parameter was calculated using the formula in Equation 3:

$$Frequency\ Ratio\ (FR) = \left(\frac{Gully\ Pixels\ in\ Class}{Total\ Gully\ Pixels}\right) \times \left(\frac{Total\ Pixels\ in\ Class}{Total\ Area\ Pixels}\right) \quad (3)$$

This computation was performed within ArcGIS by applying conditional raster extraction and zonal statistics tools. The numerator of the equation represents the proportion of gully occurrences within a particular class of a factor, while the denominator represents the proportion of the study area occupied by that class. An FR value greater than 1.0 implies that gully formation is more likely to occur in that class than would be expected by random distribution, indicating a positive association. Conversely, values below 1.0 indicate a negative association or low susceptibility.

The quantification process began with the standardization of each factor to a consistent spatial resolution of 30 meters and alignment within the WGS 1984 UTM Zone 32N coordinate system. This ensured that all rasters were compatible for cell-by-cell multiplication, a prerequisite for spatial computation of the RUSLE model (Equation 4):

$$A = R \times K \times LS \times C \times P \quad (4)$$

where A represents the estimated average annual soil loss (tons per hectare per year).

The multiplication of the five raster layers was executed in ArcGIS using the Raster Calculator tool within the Spatial Analyst extension. Each pixel in the resultant raster represented the estimated soil loss at that location, thereby generating a spatially continuous surface of soil erosion estimates for the entire study area.

To facilitate statistical evaluation, the continuous raster of soil loss was subjected to image statistics to compute summary metrics such as mean, minimum, maximum, and standard deviation of soil loss values.

3. Results and Discussion

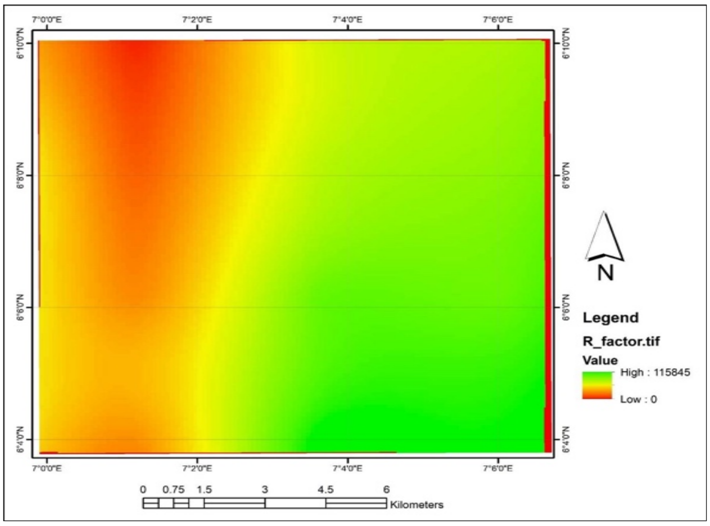
This study quantitatively assessed soil erosion dynamics in Agulu-Nanka and its environs using GIS-based RUSLE modeling and frequency ratio analysis. The Rainfall Erosivity Factor (R-factor) exhibited very high values across the study area, ranging from 0.00 to 115,845.28 MJ-mm/ha-hr-yr, with a mean of 110,562.09 MJ-mm/ha-hr-yr, indicating the dominance of high-energy rainfall events as a primary erosion driver (Figure 4). This is in line with the work of [17] who noted that high significant amounts of rainfall lead to a rapid recharge of groundwater resources in erosion prone areas. Soil erodibility (K-factor) values ranged from 0.00 to 2.00, with a mean of 1.39, revealing that a substantial proportion of soils are moderately to highly susceptible to detachment, particularly sandy and loamy textures. This result is in accordance to the study carried out by [20] in which the soil erodibility (K) factor measures showed spatially opposite pattern over R, which found to be maximum 0.3 – 0.37thMJ-1 mm-1.

Topographic influence, expressed through the LS-factor, varied between 0.00 and 7.98, with a relatively low mean of 0.135, reflecting generally gentle terrain (Figure 4). However, localized steep slopes significantly elevated erosion risk, as confirmed by Frequency Ratio (FR) analysis, when LS values greater than 4.00 recorded an FR of 2.21, indicating more than double the likelihood of gully formation compared to flatter areas. t

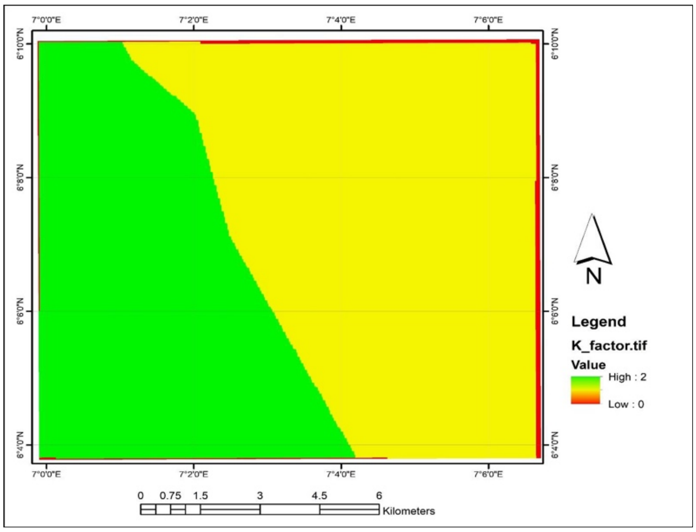
Land cover conditions strongly influenced erosion susceptibility. The Cover Management Factor (C-factor) ranged from 0.00 to 0.50, with a mean of 0.073, suggesting that while much of the area benefits from vegetative protection, disturbed and bare surfaces substantially increase erosion risk. Poorly vegetated areas (C > 0.35) recorded the highest gully susceptibility with an FR of 2.41, whereas densely vegetated zones showed low susceptibility (FR = 0.42). [21] argued that land cover is a fundamental property in sediment connectivity assessment for its influence in sediment production and mobility. The interrelation of surface coverage, runoff and soil erosion influences the sediment connectivity pattern by affecting the availability and the displacement of the sediment.

Support practice effectiveness (P-factor) values ranged from 0.55 to 1.00, with a mean of 0.575, indicating uneven application of soil conservation measures. Areas lacking conservation practices (P > 0.90) exhibited high gully occurrence likelihood (FR = 2.18), while areas with contouring practices (P = 0.55 – 0.60) showed reduced risk (FR = 0.49).

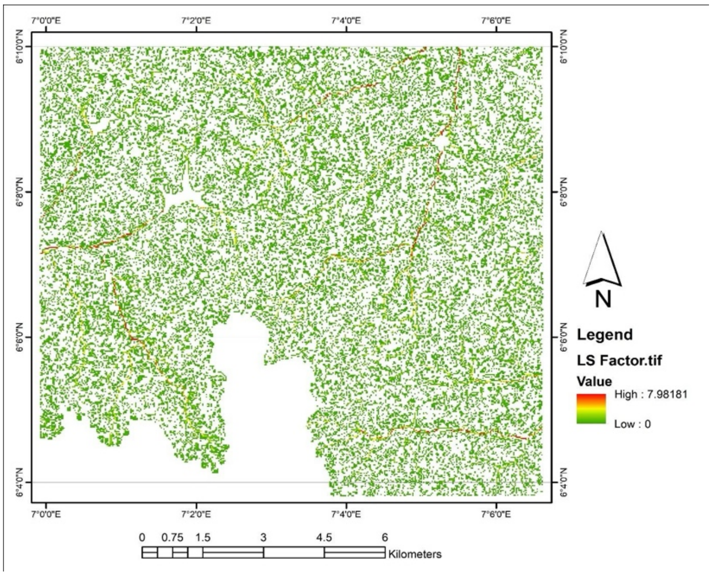
Integration of the five RUSLE parameters produced an estimated annual soil loss ranging from 0.00 to 86.34 t/ha/yr. Spatial classification of erosion risk revealed that 84.73% (119.50 km2) of the study area falls within the low-risk category, 11.36% (16.02km2) within moderate risk, 3.40% (4.79 km2) within high risk, and 0.51% (0.73 km2) within the very high-risk category. Despite their limited spatial extent, high and very high-risk zones represent critical erosion hotspots closely associated with steep slopes, high rainfall erosivity, erodible soils, sparse vegetation, and inadequate conservation practices.



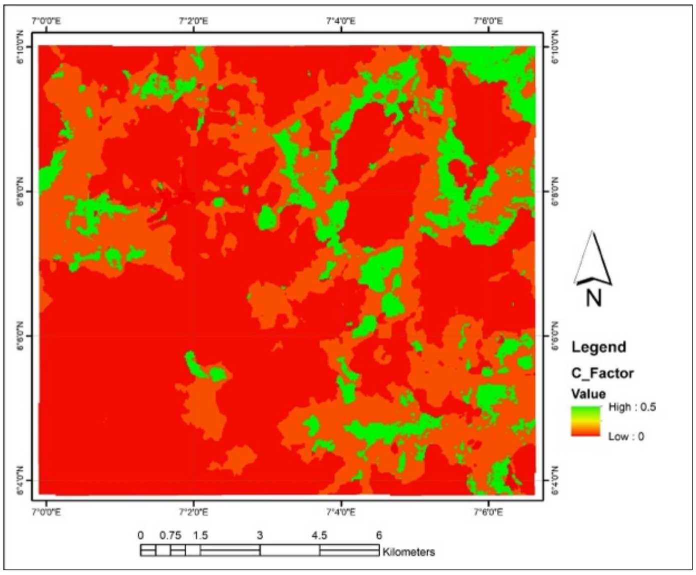
Rainfall Erosivity Factor of Agulu-Nanka



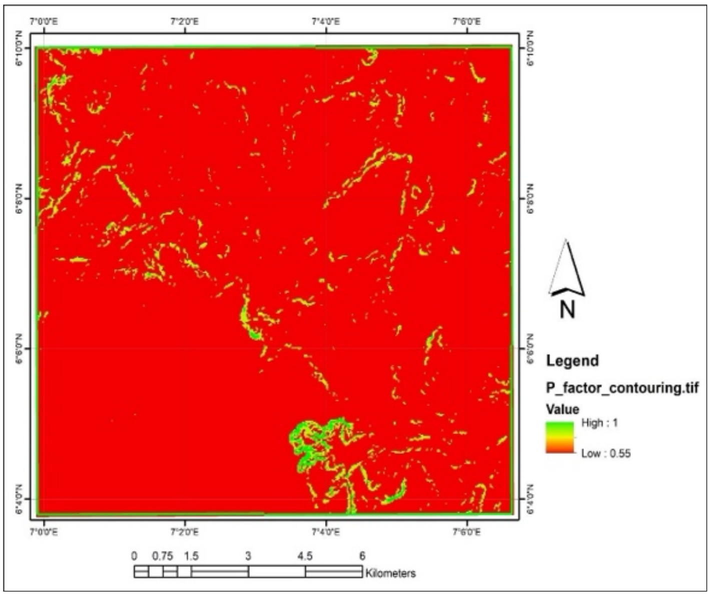
Soil Erodibility Factor (K-Factor) of Agulu-Nanka



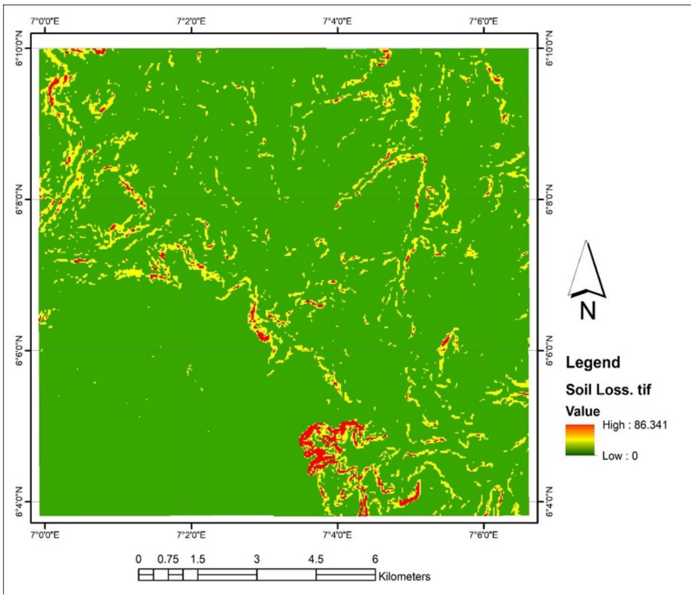
Topographic factor (LS) of Agulu-Nanka



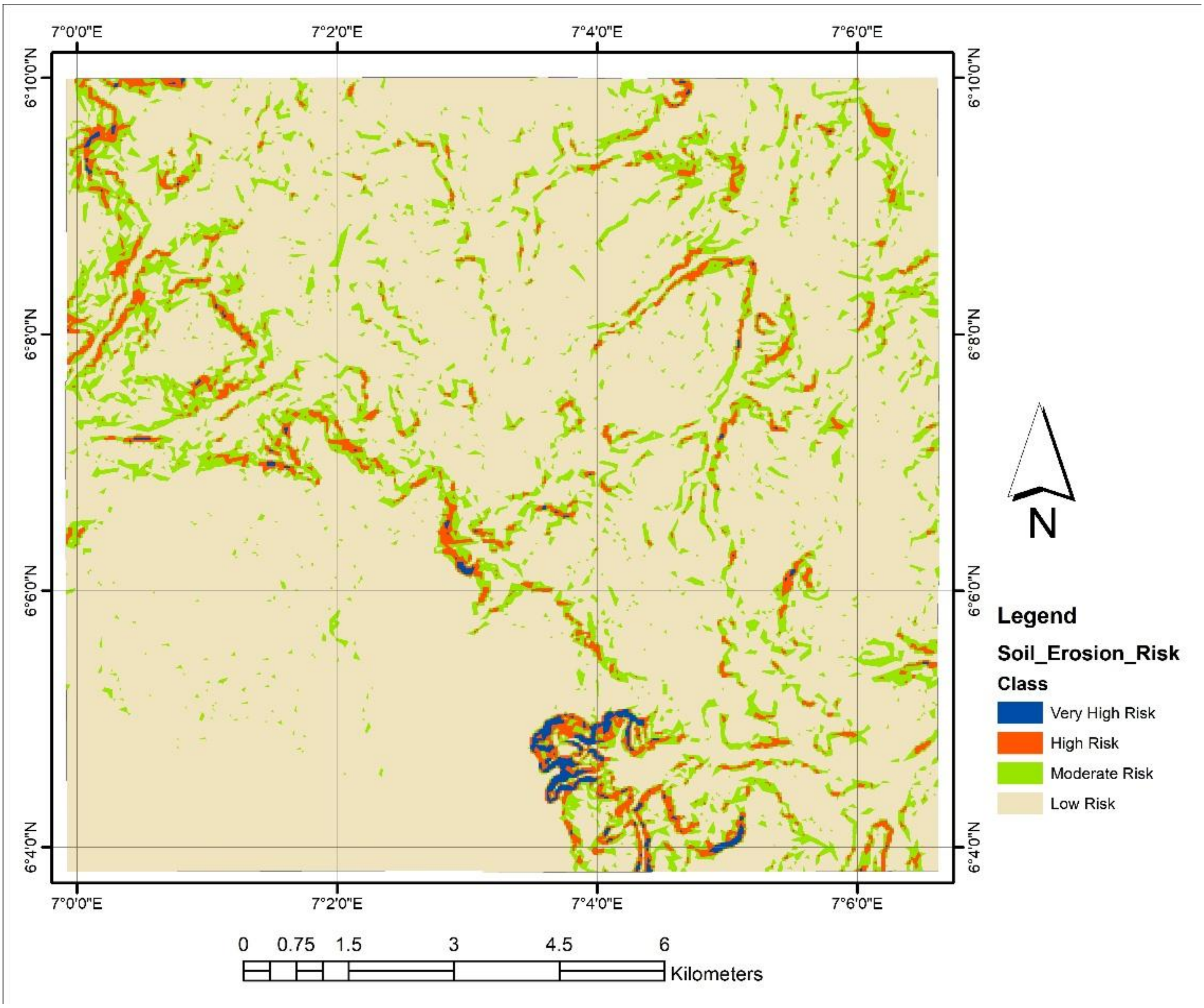
Cover Management factor (C) of Agulu-Nanka



Support Practice Factor (P) of Agulu/Nanka



Soil Loss in Agulu-Nanka



Soil Erosion Risk in Agulu/Nanka and Environs

Figure 4. Soil erosion risk imageries.

The findings quantitatively confirm that soil erosion in the study area is a multi-factorial process driven by the interaction of climatic, edaphic, topographic, and land use conditions. The integration of RUSLE and Frequency Ratio modeling provides a robust empirical framework for identifying erosion hotspots and prioritizing targeted soil conservation and gully mitigation interventions.

4. Conclusion

This study demonstrates that soil erosion in Agulu-Nanka is a severe, spatially variable environmental problem driven by intense rainfall, highly erodible soils, localized steep slopes, poor vegetation cover, and weak conservation practices. Extremely high rainfall erosivity (mean R = 110,562.09 MJ-mm/ha-hr-yr), coupled with moderately to highly erodible soils (mean K = 1.39), creates conditions favourable for extensive soil loss and gully development, particularly in escarpment zones where gully occurrence is more than twice as likely (FR = 2.21). Disturbed land cover and inadequate conservation measures further amplify erosion risk, with poorly vegetated areas and unmanaged lands recording high gully susceptibility (FR > 2.0). Estimated soil loss reaches 86.34 t/ha/yr in erosion hotspots. Although low risk areas dominate the landscape (84.73%), high and very high-risk zones covering less than 4% of the area pose disproportionate threats to agriculture, infrastructure, and livelihoods. The integrated RUSLE-FR framework proved effective for identifying erosion hotspots and supporting evidence-based land management.

To mitigate erosion, priority should be given to high-risk zones through structural measures such as terracing, contour bunds, check dams, and gully stabilization. Vegetation restoration through reforestation, agroforestry, and cover management should be intensified, alongside the promotion of soil-friendly farming practices including contour farming and minimum tillage. Erosion risk maps should be mainstreamed into land use planning and regulatory enforcement, while community participation and awareness should underpin conservation efforts. Continuous geospatial monitoring and further research using higher-resolution data and climate-integrated models are recommended to enhance long-term erosion management and sustainability.

6. Declarations

6.1. Author Contributions

Ukah Chinomso: Conceptualization, Methodology, Formal analysis, Writing - Review & Editing; **Mmelichukwu Oluebube Adieme:** Software, Validation; **Prosper Chinonso Ojukwu:** Investigation, Supervision; **Nwobu Deborah Ebere:** Resources, Data Curation; **Jennifer Ifeoma Udeh:** Project administration.

6.2. Institutional Review Board Statement

Not applicable.

6.3. Informed Consent Statement

Not applicable.

6.4. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.5. Acknowledgment

Not applicable.

6.6. Conflicts of Interest

The authors declare no conflicts of interest.

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