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Assessment of Soil Erosion Susceptibility using Multi-Criteria Analysis

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Soil erosion is a significant challenge for the environment and economy, especially in erosion-prone areas which makes sustainable soil management very crucial. This study uses the Universal Soil Loss Equation (USLE) to identify areas susceptible to soil erosion and estimate soil loss. The USLE considers various factors, such as slope characteristics, vegetation management, soil erodibility, and rainfall erosivity. It uses several data sources like soil composition, precipitation patterns, digital elevation models, land usage, and vegetation cover. The study classified erosion-prone zones into low, medium, high, and very high vulnerability categories using the Analytical Hierarchy Process (AHP) as part of a multi-criteria analysis. The findings reveal that the study area experiences an average annual soil loss rate of 3186.6 tonnes per hectare per year. While 83.3% of the study area has the lowest soil loss rate, though the regions could still be vulnerable to erosion due to steep slopes, high rainfall, and gullies. The Geographic Information System, USLE, and diverse data sources help identify erosion-prone areas with potential soil loss. The study's results are valuable for policymakers and farmers as they provide a foundation for targeted strategies to prevent erosion in the study area and similar regions.

Keywords: Analytical Hierarchy Process, Digital Elevation Model, GIS-based Multi-Criteria Analysis, Land Use Cover, Soil Erosion, Universal Soil Loss Equation

<https://dx.doi.org/10.4314/etsj.v15i1.4>

INTRODUCTION

Soil erosion is a major global issue that poses various challenges due to its wide-ranging impacts such as road destruction, river sedimentation, land degradation, and compromised water quality (Ping *et al.*, 2020). It affects the environment, human health, and agricultural productivity by causing a depletion in soil quantity and quality, and water pollution (Soilerosionst, 2019). Alarming statistics reported by the FAO's Global Soil Partnership reveal that every year, 75 billion tons of arable soil are lost, equating to staggering revenue losses of approximately \$400 billion (Borrelli *et al.*, 2017). This loss has dire consequences for farmers' livelihoods and exacerbates food scarcity (Prasannakumar *et al.*, 2012; Ullah *et al.*, 2018). The Revised Universal Soil Loss Equation (RUSLE), which is an updated version of USLE, is a model that deals with complicated scenarios involving rill and inter-rill erosions by substituting runoff for rainwater (Djoukbal *et al.*, 2018). USLE is, however, particularly useful in addressing precursor erosion forms such as sheet and rill erosion to prevent future gully erosion. It is especially suitable for agricultural regions where these forms of erosion are common (Gelagay & Minale, 2016).

The accurate estimation of soil erosion necessitates not only field expertise but also sophisticated modelling techniques such as USLE and RUSLE (Kefi *et al.*, 2010; Renard *et al.*, 1997), often integrated with remote sensing technologies and Geographic Information Systems (GIS) (Yoshino & Ishioka, 2005; Leh *et al.*, 2013). GIS and Remote Sensing (RS) are pivotal in

assessing soil erosion dynamics, facilitating data collection, computation of soil loss, multi-criteria decision analysis, and spatial visualization of erosion patterns (Patil *et al.*, 2016). Several studies on RS and GIS technologies to evaluate soil erosion losses, indicating variations in annual soil loss influenced by land use changes have been conducted (Ganasri & Ramesh, 2016; Fu *et al.*, 2017; Tadesse *et al.*, 2017; El Jazouli *et al.*, 2019). While some of these studies emphasized the role of human activities or anthropogenic forces in sediment discharge changes over climate change (Sun *et al.*, 2013), the integration of USLE, RS, and GIS in this study offers a comprehensive approach to assess soil erosion susceptibility and develop effective prevention and control strategies. This study adopts a multi-criteria analysis approach, particularly the Analytic Hierarchy Process (AHP) (Vassoney *et al.*, 2021), in conjunction with USLE, to evaluate areas prone to erosion with the primary aim of empowering stakeholders with crucial information for proactive soil erosion management.

MATERIALS AND METHODS

Study area

The teaching and research farm of the Federal University of Technology, Minna, Nigeria was used as the study area. The university campus encompasses a vast area of 18,900 hectares, strategically positioned at the kilometre-10 mark of the Minna-Bida Road, southeast of Minna (Musa *et al.*, 2012). The study area is geographically bounded by approximately 9° 30' 58"N to 9° 31' 06"N latitude and 6° 26' 30.43"E to 6°

26' 29''E longitude, as illustrated in Figure 1. The primary socio-economic activities within this region are farming and academic pursuits. The size of the study

area is approximately 4.6 hectares. This area was carved out for this study due to past experiences with erosion, particularly gully erosion.

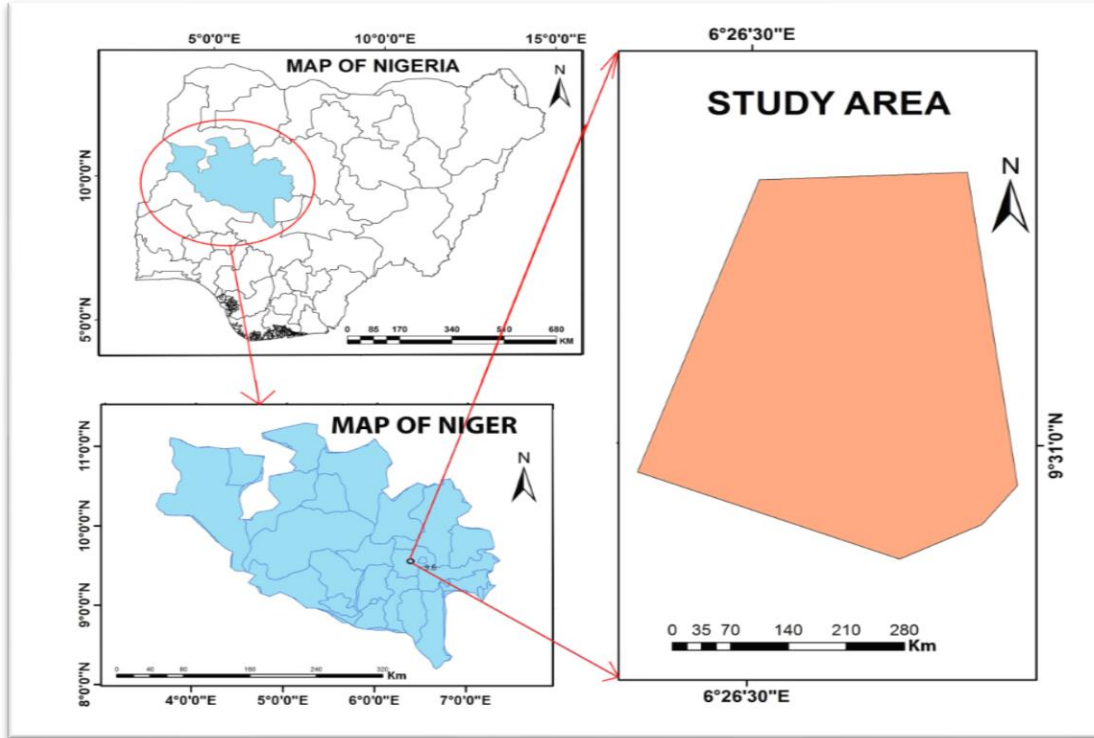


Figure 1: Study area showing its location in Niger State and the location of Niger state in Nigeria

Data Used

A summary of the data used for this study and their sources is presented in Table 1. The data used include

satellite images, rainfall data, soil type and topographic data (spot heights) of the study area.

Table 1: Data used and their sources

S/N	Data list	Data type	Data source	Data Use	Month/Year
1	Satellite Imagery	Secondary data	Google Earth Pro: 9m resolution (http://maps.google.com/?ll=9.51739,6.44139&z=16&t=h)	Creating land use and land cover maps for the determination of cover management and supporting practice factors.	June/2021
2	Spot heights	Primary data	Field observation	Producing the slope of the study area for the determination of slope length and steepness.	June/2021
3	Rainfall	Secondary data	NASA Langley Research Center (LaRC) Power Project funded through the NASA (National Aeronautics and Space Administration) Earth Science/Applied Science Program(https://power.larc.nasa.gov/data-access-viewer/)	Determining the rainfall erosivity of the study area	Jan-Dec/2009-2019
4	Soil Type	Secondary Data	A shape file of the Digital Soil Map of the World (DSMW) from Food and Agriculture Organization (FAO)Geo-Network; (http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116)	Determination of soil erodibility in the study area	June/2019

Methods

This section summarises the parameters used in this study and the procedure for the implementation of Universal Soil Loss Equation (USLE) and Multi-Criteria Analysis.

Universal soil loss equation (USLE)

The USLE model comprises the following parameters: rainfall erosivity, soil erodibility, slope length or steepness of plant cover and agricultural methods, and erosion control measures. Figure 2 depicts the step-by-step procedure involved in the implementation of USLE.

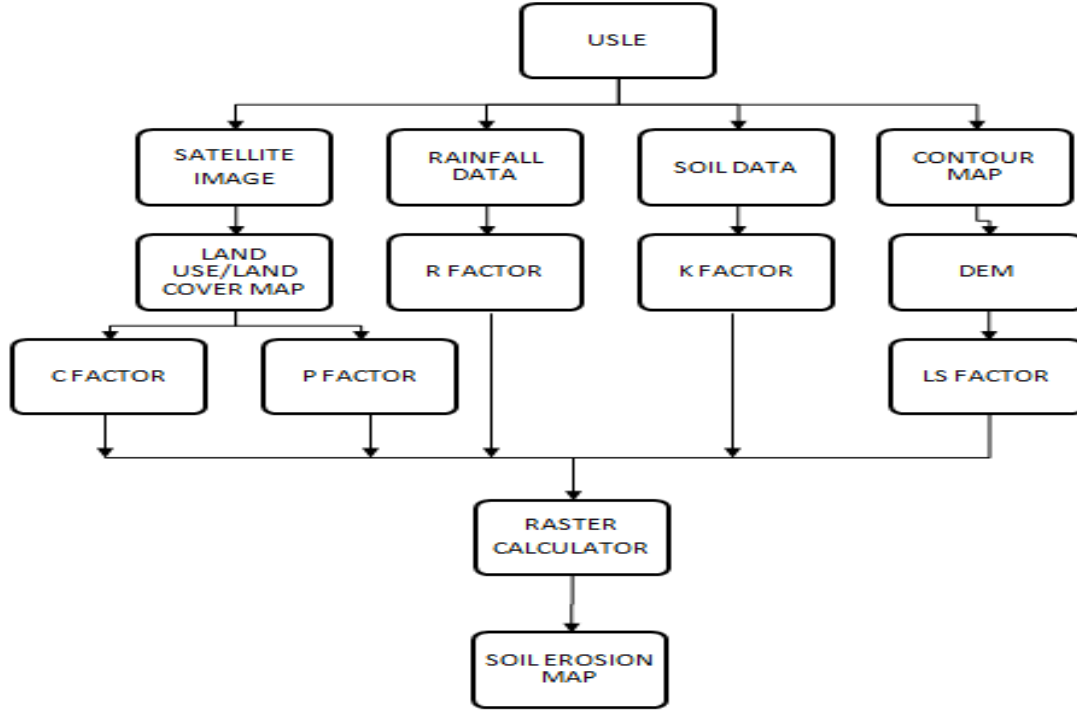


Figure 2: The USLE's workflow schematic

The quantity of soil loss (soil erosion) was computed using the Universal Soil Loss Equation (USLE) shown in Equation (1) (Kelsey & Johnson, 2015).

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

Where,

(A) = Estimated soil loss ($t/ha/yr$)

(R) = Rainfall erosivity factor ($MJmmha^{-1}h^{-1}$)

(K) = Soil erodibility factor ($tha^{-1}MJ^{-1}mm^{-1}$)

(LS) = Slope length or steepness factor (dimensionless)

(C) = Plant cover and agricultural methods/Cover management factor (dimensionless)

(P) = Erosion control measures/Support practice factor (dimensionless)

Rainfall erosivity factor (R)

Rainfall erosivity is an index that measures how well rainfall erodes soil. It evaluates and forecasts soil erosion rates in agricultural fields (Nearing *et al.*, 2017). Equation (2) (El Jazouli *et al.*, 2017) presents the formula for determining rainfall erosivity.

$$\log R = 1.74 \times \log \sum \left(\frac{P_i^2}{P} \right) + 1.29 \quad (2)$$

where,

R = Erosivity factor in $(M)mmha^{-1}h^{-1}year^{-1}$

P_i = Monthly rainfall (mm)

P = Annual rainfall (mm)

Soil erodibility factor (K)

Soil erodibility is an estimate of the ability of soils to resist erosion based on the physical characteristics of each soil (Ritter, 2012). Earth erodibility factor was estimated using Equation (3) (Karamage *et al.*, 2016).

$$K = 2.1 \times 10^{-6} * M^{1.14} \times (12 - OM) + 0.0325 \times (P - 2) + 0.025 * (S - 3) \quad (3)$$

where:

M = (% silt + % veryfinesand) (100% clay)

OM = Percentage of organic matter

P = Permeability Class

S = Structure Class

Slope length/Steepness factor (LS)

This factor describes the effect of topography on soil erosion (European Union, 2015). Ground truthing was done by directly measuring spot heights in the field to create a DEM, from which contour and slope maps of the study area were generated, and which was used to

derive the steepness factor using the raster calculator of ArcMap. The mathematical equation used in determining the slope length/steepness ratio is presented in equation (4) (Nwaogu *et al.*, 2018).

$$LS = (QaM/22.13)^y * (0.065 + 0.045xSg + 0.0065 xSg^2) \tag{4}$$

where;

LS = Slope length/Steepness factor

Qa= grid for accumulating flow

Sg= % grid slope

M= size of the grid (Vertical length times horizontal length)

y is a constant that depends on the grade of the slope; it is 0.5 for slopes higher than 4.5%, 0.4 for slopes between 3.5% and 4.5%, 0.3 for slopes between 1% and 3%, and 0.2 for slopes less than 1%.

Cover management factor(C)

Supervised image classification was performed on the satellite images using a maximum likelihood classifier

to produce the Land Use Land Cover (LULC) to determine the cover management factor (C). The study area’s LULC classes are Gully, Built-up, Vegetation and Soil. The erosion ratio under specific cover and management is the (C) factor (FAO, 2021). (C) factor values vary by region and country due to different (R) factors (Rainfall erosivity). The values used in this study are presented in Table 2 and provided by Nwaogu *et al.* (2018), which was derived from similar land cover types in the same country (Kelsey *et al.*, 2015).

The cover management factor (C) from the Normalized Difference Vegetation Index (NDVI) of the region through regression correlation analysis was generated using Equation (5) (Van der Knijff *et al.*, 2000; Benavidez *et al.*, 2018).

$$C = \exp[\alpha (\frac{NDVI}{\beta-NDVI})] \tag{5}$$

where

$$\alpha = 2$$

$$\beta = 1$$

Table 2: Land use-land cover and C factor table

Land use-land cover	(C) factor
Gully	0.98
Built-up	0.99
Vegetation	0.72
Soil	0.86

Supporting practices factor (P)

The recommendations of Moore and Wilsons (1992) which were used by Nwaogu *et al.* (2018) are adopted in this study for the derivation of the supporting practices factor (P), with the factor representing soil loss ratios considering management strategies that affect erosion flow (Benavidez *et al.*, 2018). The numbers depicting this factor ranges from 0 to 1, with 0

indicating excellent erosion protection and 1 indicating none. Various artificial erosion protection methods, like strip cutting and contouring, have distinct values. Terracing, widely used by local farmers, has different factor values based on slope angle classifications (Karamage *et al.*, 2016). Table 3 presents the terracing support practice component (P).

Table 3: Terracing support practice component (P)

Slope (%)	(P) Factor
0 - 7	0.1
7 - 11.3	0.12
11.3 - 17.6	0.16
17.6 - 26.8	0.18

Multi-Criteria Analysis

The Analytical Hierarchy Process (AHP) method prioritized erosion-prone areas via pair-wise comparison for studying erosion factors (Zlaugotne *et al.*, 2020). The factors included land use and vegetation,

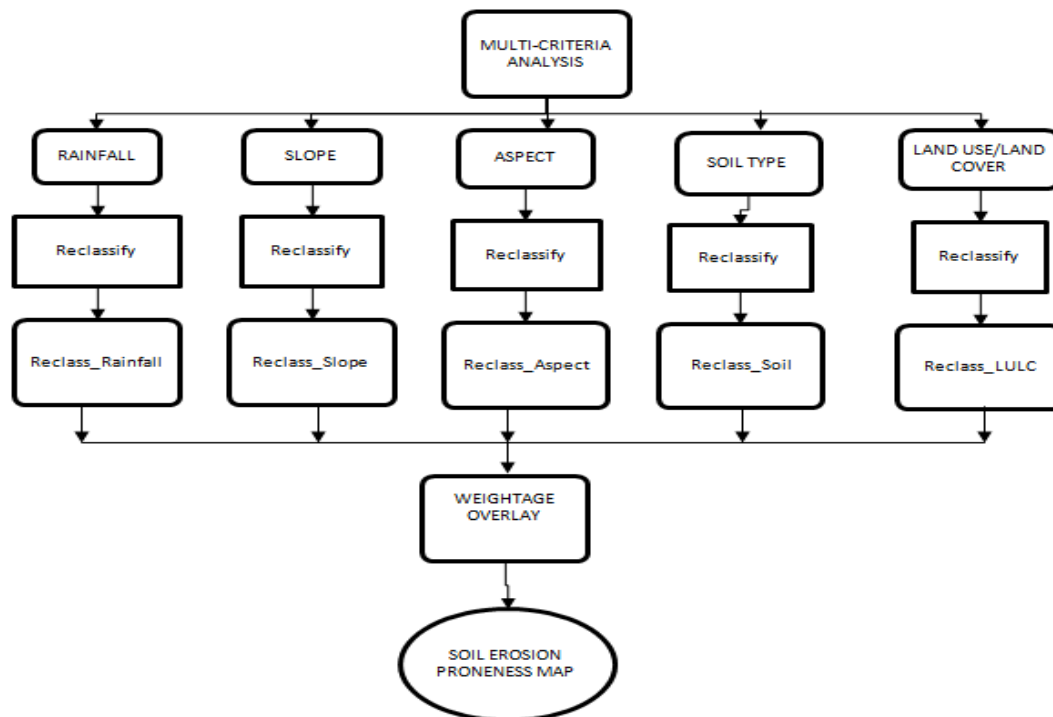
rainfall, slope, aspect, and soil type. Using Saaty’s pair-wise comparison measure, the weights for each criterion were found ((Mu & Rojas, 2017; Ajayi *et al.*, 2022). Table 4 displays the pair-wise comparison matrix showing the weight criteria and rates.

Table 4: Pairwise comparison matrix

Criteria	Rainfall	Slope	Aspect	Soil Type	Land Use
Rainfall	1	2	3	5	7
Slope	1/2	1	3	4	6
Aspect	1/3	1/3	1	3	5
Soil Type	1/5	1/4	1/3	1	5
Land Use	1/7	1/6	1/5	1/5	1
Total	3.5928	3.7499	7.5333	13.2	24

According to Saaty's pair-wise comparison scale, 1, 3, 5, 7, and 9 are important values signifying, middling significance, strongly important, very strongly important, and exceedingly important values, respectively. Consistency analysis was carried out after the weights to ensure the calculated values of the

pairwise and normalized pair-wise matrices are accurately computed. The consistency ratio (CR), random (RI) and consistency index (CI) were used to ascertain the test consistency. The multi-criteria analysis task flow is presented in Figure 3.

**Figure 3: Multi-criteria analysis workflow****Consistency index (CI)**

The consistency index (CI) was estimated using Equation (6) (Halefom *et al.*, 2018).

$$CI = [\lambda^{\wedge}max - n]/[n - 1] \quad (6)$$

Where $\lambda^{\wedge}max$ is the average of each criterion's weighted total number and criteria weight ratio. A consistency index value of 0.02045 was obtained.

Random index (RI)

The coherence-paired matrix is generated at random and measured by a random index. It is a constant chart with predetermined numbers for the different factors. The random index constants for the appropriate number of conditions are presented in Table 5. This study used a total of 5 factors, making the random index used for this study 1.12.

Table 5: RI (Random Index) chart

Size	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

(Source: Ammarapala *et al.*, 2016)

Consistency Ratio (CR)

The consistency ratio (Equation 7) was obtained by dividing the consistency index (0.02045) by the random index (1.12). Each thematic layer is re-classified by the weighted overlay tool to create the soil erosion-proneness region map using the determined weights (Mu & Rojas, 2017).

$$CR = CI/RI \quad (7)$$

where, *CI* is the Consistency Index, and *RI* is the Random Index.

The CR value obtained (1.83%) in the MCDA suggests that the inconsistency of the pairwise comparisons is acceptable. According to Saaty's recommendation, if

the CR is less than or equal to 12%, the inconsistency can be considered acceptable, and the judgments from the pairwise comparisons can be trusted (Ajayi *et al.*, 2022).

RESULTS AND DISCUSSION

The study explores geographic interactions of USLE variables causing soil erosion. Figures 4a, 4b, 5a, 5b, and 5c showing the Rainfall erosivity, soil erodibility, Length of Slope/Steepness, Cover Management, supporting practices respectively, being the USLE factor maps generated in ArcMap 10.8. The Land Cover and Use is presented in Figure 5d while Figures 6a and 6b present the Slope and Factor Maps used in the MCA method.

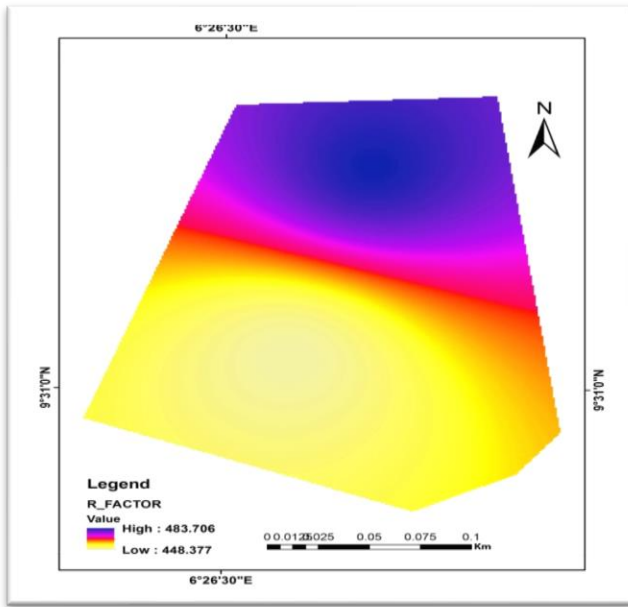


Figure 4a: Rainfall erosivity factor

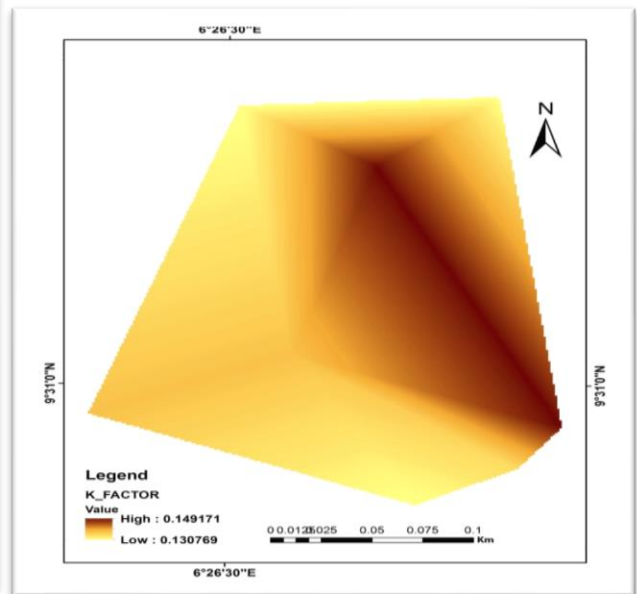


Figure 4b: Soil erodibility factor

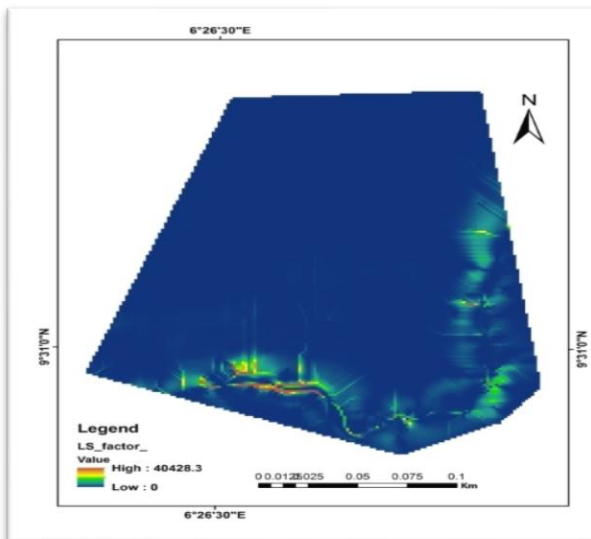


Figure 5a: Length of Slope/Steepness Factor

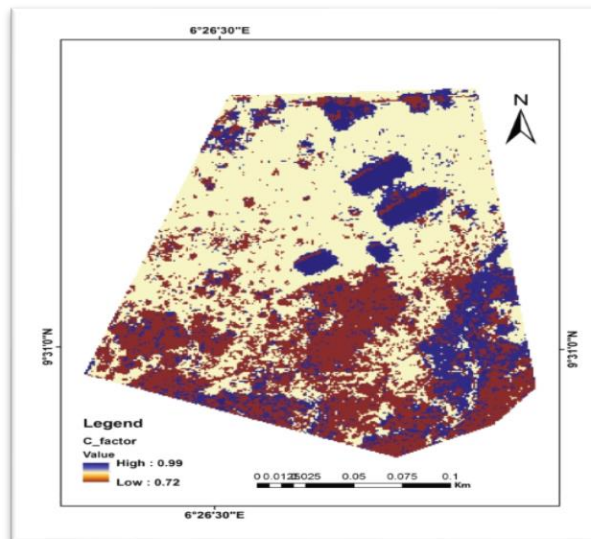


Figure 5b: Cover management component

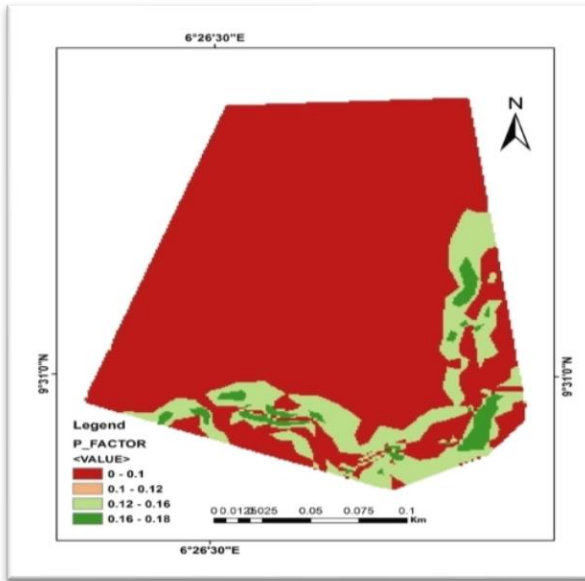


Figure 5c: Factor supporting practice

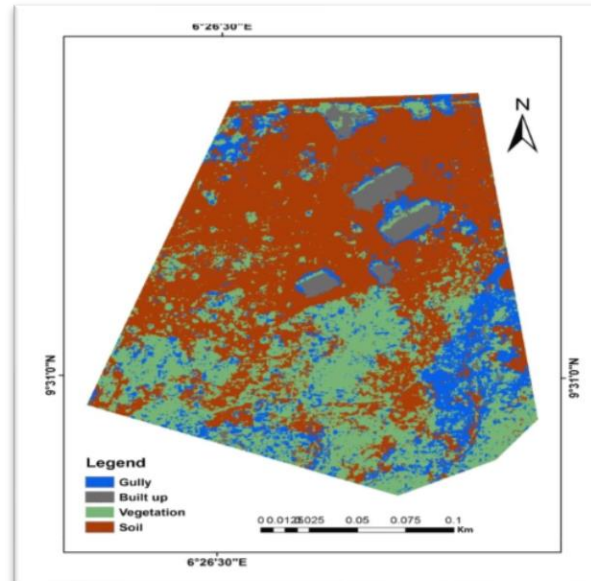


Figure 5d: Land Cover and Use

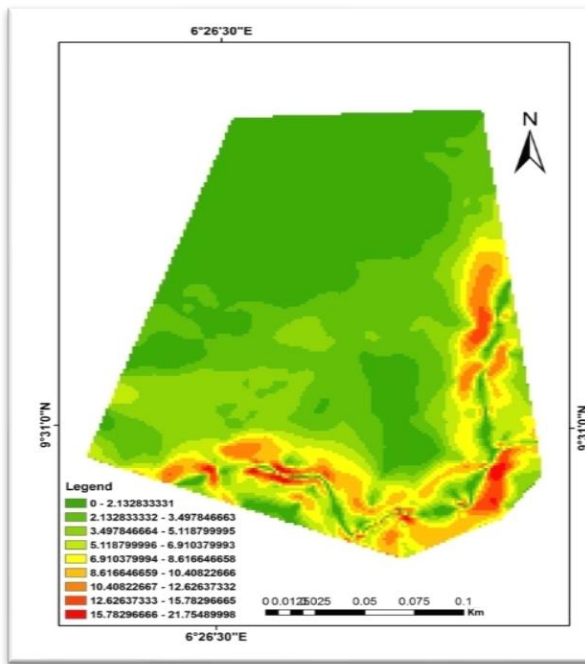


Figure 6a: Map of the slope

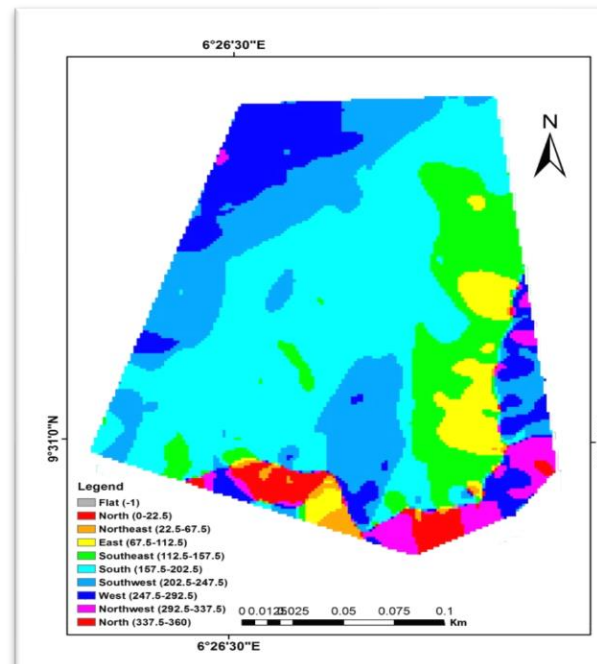


Figure 6b: Aspect Map

Figure 4a depicts how the rainwater erosivity component is distributed spatially (R). The study area's location with the greatest rainfall has a value of 483.706 mm, which shows that this area will experience greater soil erosion than other areas and that more soil will be lost from this area. The region with the highest soil erodibility, 0.149171, is shown in Figure 4b. This area also experiences significant rainfall. This region has more silt content than other soil types because silt is the most erodible soil variety (sand, clay, etc.). This might result in significant soil erosion in the region.

Figure 5a shows the study area's (LS) factor, which is very high due to the area's extremely steep inclination (22°). The region with the highest soil loss is due to a gully and steep slope. The factor map's geographic spread is depicted in Figure 5b. The gully class has the greatest rate of soil loss in the study area (0.99), which indicates that a significant quantity of soil is lost.

The factor map's (P) geographic spread is shown in Figure 5c and its (P) factor values are spread according to the different classes of slope. A steeper slope has a greater (P) value, and this is found in the vicinity of

areas with gullies. The LULC grid is shown in Figure 5d, from which the (C) component was calculated.

The slope chart is presented in Figure 6a in degrees. In comparison to aspect, soil type, and LULC, the study area has a very steep inclination, making it more susceptible to soil erosion. Rainfall poses a greater risk than an incline because it causes runoff, particularly in sloppy regions. These factors were taken into consideration when finding the soil runoff susceptibility using MCA.

The aspect map of the study area is displayed in Figure 6b. The aspect map faces the south because the predominant colours are light green, light blue, and blue (if it faces the north, the predominant shades would be purple, red, and orange, as shown in the map's caption).

Due to the low soil moisture content and south-facing side of the study area, it is less erodible but also more vulnerable to erosion because of the lack of vegetation. As a result, when using MCA to identify regions susceptible to soil erosion, the vulnerability of the aspect to soil erosion is smaller or less impactful when compared to rainfall.

Four levels of severity were assigned to the soil loss measurement map: very high, high, medium, and low (Subin, 2012). The soil erosion class and chart are shown in Figure 7. According to Table 6, regions with low soil loss rate make up 83.3% of the study area, while those with middle, high and very high soil loss rate account for 8.2%, 5.1%, and 3.4% of the study area, respectively.

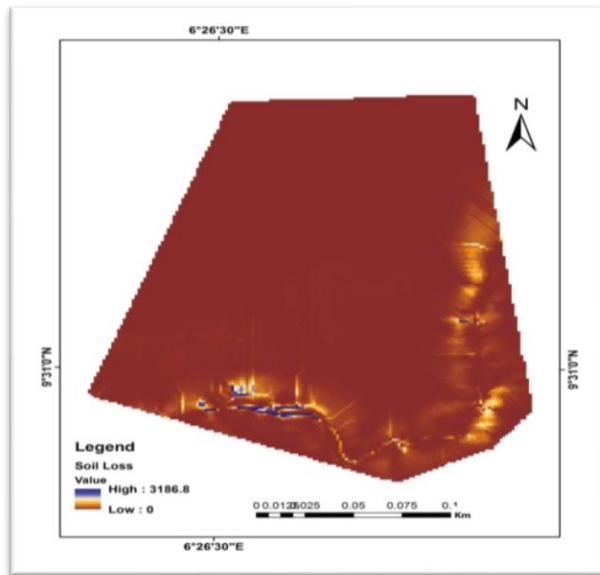


Figure 7: Soil loss Map

The gully area, comprising 3.4% of the study area, exhibits the highest soil loss rate indicated in Figure 7. Soil loss is primarily caused by steep slopes and heavy rainfall, leading to gully formation and surrounding soil loss. Figure 8 shows that low soil erosion-prone regions have moderate slopes, minimal rainfall, and less

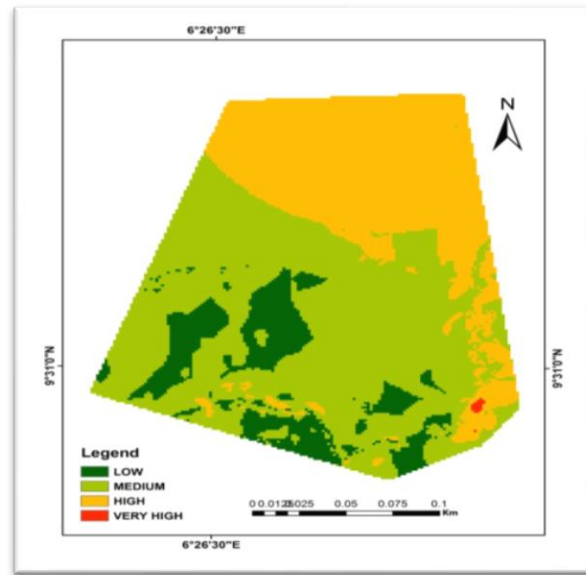


Figure 6: Soil runoff susceptibility

erodible soil. Medium erosion-prone areas have moderate rainfall, fairly erodible soil, and slight slopes with appropriate plant cover, high and very high erosion-prone regions are characterized with rainfall, steep slopes, and erodible soil.

Table 6: The study area's soil erosion statistics

Erosion class	Soil erosion rate (tons/hectare/yrs.)	Area (m ²)	Percentage (%)
Low	0 - 63.2	44274.2	83.3
Medium	63.2 - 575.7	315.2	8.2
High	575.7 - 1625.6	47.6	5.1
Very High	1625.6 - 3186.8	22.7	3.4

MCA combined weighted layers such as rainfall, elevation, aspect, soil type, and LULC to create the soil erosion-prone map (Figure 8). The study area was stratified into four categories: low, middle, high, and

very high. 13% of the area has minimal soil erosion proneness, 50% has medium proneness, 33% is high, while 4% is very high (Table 7).

Table 7: Study location with a high risk of erosion

Erosion class	Area(m ²)	Percentage (%)
Low	5510.7000	13
Medium	24003.4000	50
High	15198.1000	33
Very High	50.5881	4

CONCLUSION

The identification of high and very high soil erosion-prone locations in the study area underscores the significant influence of heavy rainfall, variable slope gradients, and erodible soil. These factors likely contributed to the formation of the observed gully, particularly in the vicinity where higher values were noted. The study noted that about 33% and 4% of the study area are very susceptible to flood while about 50% boasts of moderate susceptibility. Only 13% of the entire study area poses low risk to soil erosion. These findings show that there is need for the urgent introduction of mitigation strategies to prevent soil loss and other forms of land degradation in the study area. The insights garnered from this study is of high significance to land users, particularly farmers, enabling them to devise sustainable soil erosion management strategies and make informed decisions on soil utilization and preservation. While the soil erosion quantification chart suggests a low overall risk of soil erosion in the region, the susceptibility to soil erosion remains due to the presence of gullies, steep terrain, and heavy precipitation. As observed in the study area, erosion-prone areas surround gullies and mild hills, emphasizing the importance of implementing strategies such as maintaining dense vegetation cover in these regions. Such practices serve as a precautionary measure to reduce the erosive impact of rainfall and soil erodibility. Additional measures, such as strip trimming and contouring, can complement erosion prevention efforts.

The Multi-Criteria Analysis (MCA) framework employed for soil erosion prediction equips the study with effective tools for long-term soil erosion control and better land management. This study's successful utilization of the Universal Soil Loss Equation (USLE) and MCA validates their effectiveness in estimating soil loss and identifying vulnerable areas. The findings reaffirm that soil erosion is accelerated by factors like steep slopes, intense rainfall, and soil erodibility, elucidating the presence of the gully within the study area.

The broader implications extend to farmers who can leverage on these techniques to identify erosion-vulnerable zones and implement preventive measures,

averting the detrimental effects of erosion. Given the impact of human practices on soil erosion, prudent land use planning such as locating agricultural activities away from urban centres, can mitigate human-induced erosion in vulnerable areas. Moreover, embracing conservation measures within forested areas is crucial to curbing soil runoff in specific regions.

Conflicts of interest

The authors affirm that they have no competing interests.

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