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Research Article

Analysis of Areas Susceptible to Gullies in Ideato South Local Government Area of Nigeria Using Geographic Information System and Remote Sensing Technology

Sylvanus Iro

Department of Geography and Environmental Management, Imo State University, Owerri, Nigeria

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Corresponding Author:
Sylvanus Iro
Department of Geography and Environmental Management, Imo State University, Owerri, Nigeria
Email: sylvanusiro@gmail.com

Abstract: Gully erosion is a critical environmental hazard in Southeastern Nigeria, threatening agricultural productivity, infrastructure, and communal safety. This study provides a spatially explicit assessment of gully erosion susceptibility in Ideato South Local Government Area (LGA), Imo State, using an integrated Geographic Information System (GIS) and Remote Sensing framework. The methodology employed a multi-criteria decision-making approach, utilizing the Analytical Hierarchy Process (AHP) to weight thirteen geo-environmental conditioning factors, including topography, hydrology, rainfall, soil properties, and Land Use/Land Cover (LULC). These factors were standardized and integrated through a weighted overlay technique to produce a Gully Erosion Susceptibility Map (GESM). The results demonstrate that LULC (19%) and soil properties (15%) are the most significant drivers of erosion in the region. Spatial analysis reveals a landscape highly predisposed to degradation: Approximately 57% (34.33 km²) of the LGA is classified as having "Slight" to "Very High" susceptibility. Notably, 12% (7.25 km²) and 0.17% (0.10 km²) of the land area are categorized as "High" and "Extremely" susceptible, respectively. These high-risk zones are primarily concentrated in areas characterized by steep slopes, high flow accumulation, and intense anthropogenic disturbance. The findings provide a robust evidence-based framework for environmental planners to implement targeted soil conservation measures and sustainable land-management policies in Ideato South.

Keywords: Gully Erosion, Ideato South, GIS, Remote Sensing, Analytical Hierarchy Process (AHP), Susceptibility Mapping

Introduction

Gully erosion has emerged as one of the most severe environmental challenges confronting many urban and rural communities in South-eastern Nigeria; it has become extremely dangerous for people to reside there (Iro, 2020). Hundreds of people are impacted negatively every year as erosion ruins farmlands and reduces agricultural production, and substantial portions of agricultural lands are rendered unfit for cultivation (Iro, 2020; Nwankwoala, 2019). With areas such as Ideato South in Imo State being the most affected region in Nigeria, with gullies and erosion-prone areas doubling in size from 1.33% (1,021 km^2) in 1976 to 3.7% (2,820 km^2) in 2006, with over four hundred active and dormant gully erosion sites in Imo State alone (World Bank, 2012). Gully erosion is the process by which a gully is formed by flowing water, sharply eroding through the soil, and often occurring on a hillside (Speight, 2018). Gully erosion is a typical and usually severe type of soil degradation brought on by moving surface water (Nwankwoala, 2019). It is made up of open, unstable channels that have been carved more than 30 centimetres into the soil surface. A gully may be described as a relatively permanent channel formed by concentrated surface runoff, through which water flows intermittently during periods of intense rainfall, transporting sediment downslope (Chowdhuri et al., 2020). The development of gullies is influenced by two broad categories of factors: Physical conditions, such as topography, climate, soil texture, and vegetation cover, and human-induced activities, including overgrazing, deforestation, and unregulated land-use practices (Iro, 2023; Jahantigh and Pessarakli, 2011). However, the relative importance of these factors varies spatially, meaning that gully occurrence, morphology, and erosion intensity differ across regions depending on local topographical, climatological, and hydrological characteristics (Artiola et al., 2019).

Soil erosion remains a global environmental concern due to the substantial economic losses it generates (Chowdhuri et al., 2020). Of particular importance is the removal of topsoil, the most fertile layer of the soil profile essential for agricultural productivity, which is highly vulnerable to erosion processes (Iro, 2020). The loss of this layer results in reduced crop yields and increased production costs. Furthermore, accelerated runoff associated with soil erosion removes water and nutrients that would otherwise support plant growth, contributes to the failure of newly planted crops, reduces the soil's capacity to retain moisture and nutrients, exposes subsoil layers with inferior physical and chemical properties, and leads to sediment accumulation in low-lying areas (Government, 2022). In addition, soil erosion increases turbidity in watercourses and storage systems, thereby degrading water quality in streams, rivers, and coastal environments.

Eroded soil, often enriched with nutrients, fertilisers, herbicides, or pesticides, is commonly deposited in areas where land slope decreases (Amiri et al., 2019; National Soil Erosion Research Laboratory, 2022). Such deposition typically occurs in environments including wetlands, sediment traps, contour banks, and dams (Abdulfatai et al., 2014). During this process, coarser and heavier soil particles tend to settle first, while finer colloidal clay particles may remain suspended and be transported over longer distances. In some cases, gully erosion can convey soil materials directly into streams and rivers, particularly the finer colloidal fractions.

Impervious surfaces such as bitumen, concrete, and road tracks significantly increase surface runoff (Energy and Agriculture, 2020). Where adequate stabilisation measures are not implemented, land disturbance associated with road construction can accelerate erosion and lead to downstream siltation. Similarly, urban development can trigger severe soil erosion when construction occurs on unsuitable terrain or intersects natural drainage pathways, thereby intensifying runoff and sediment transport processes (Government, 2022). Previous studies on gully erosion susceptibility, particularly in South-eastern Nigeria, have provided valuable insights into the roles of topography, soil properties, rainfall, and land use; however, several limitations remain evident. Many studies rely heavily on single-model approaches such as RUSLE or basic GIS overlay techniques, which often oversimplify the complex, non-linear interactions among erosion drivers. In addition, the weighting of conditioning factors in methods like the Analytical Hierarchy Process (AHP) is largely subjective, depending on expert judgment, thereby introducing bias and reducing reproducibility across different geographic contexts. Another key limitation is the dependence on moderate-resolution datasets (e.g., SRTM DEM), which may not adequately capture micro-topographic variations critical for gully initiation. Furthermore, validation of susceptibility maps in earlier works is often weak, relying on limited field points or lacking rigorous statistical accuracy assessment, which raises concerns about the predictive reliability of such models.

Methodologically, recent advancements have attempted to address these shortcomings through the integration of machine learning and ensemble modelling techniques, which improve prediction accuracy by capturing complex relationships among variables (Society, 2022). However, these advanced methods are often data-intensive, computationally demanding, and less accessible in data-scarce environments like many parts of Nigeria. This creates a gap between methodological sophistication and practical applicability. In contrast, this study adopts a hybrid approach by integrating GIS, Remote Sensing, AHP, and RUSLE within a low-cost and operational framework, balancing methodological robustness with contextual feasibility. Despite these improvements, a clear research gap persists in developing locally calibrated, high-resolution, and dynamically validated gully erosion models tailored to specific environmental and socio-economic conditions of areas such as Ideato South. There is also limited integration of temporal analysis to capture the evolution of gullies over time, as well as insufficient incorporation of community-based or anthropogenic variables beyond generalized land use classes. Addressing these gaps is essential for improving the accuracy, transferability, and policy relevance of gully erosion susceptibility assessments in vulnerable regions.

Statement of the Problem

Gully erosion constitutes a major environmental challenge that degrades land resources, leading to the loss of agricultural and residential areas, damage to infrastructure, and, in extreme situations, loss of human lives. In Ideato South, South-eastern Nigeria, the problem is particularly severe, with gully systems exceeding 12 m in depth and causing extensive disruption to land use, infrastructure, and local livelihoods. Although various engineering and control measures have been implemented, gully erosion persists as a critical concern, driven largely by intense rainfall events that modify surface morphology and accelerate erosional processes. During storm events, rapid gully expansion results in the destruction of productive land and significant economic losses.

Urban expansion has been identified as a key factor contributing to the intensification of gully erosion in the region; however, knowledge gaps remain regarding gully forms, developmental stages, and the susceptibility of soils to erosion in Imo State. In addition, the limited applicability and inconsistent performance of existing erosion models underscore the need for alternative, context-specific approaches to assessing soil vulnerability. In this regard, spatial analysis techniques integrating Geographic Information Systems (GIS), Satellite Remote Sensing (SRS), and geostatistical modelling are essential for predicting gully initiation and guiding sustainable land restoration efforts (Choi et al. 2016). This study evaluates soil erosion dynamics in Ideato South using a combination of acquired and derived datasets. Low-cost Remote Sensing (RS) and GIS techniques are employed alongside the Analytical Hierarchy Process (AHP), while erosion risk is quantified using the Revised Universal Soil Loss Equation (RUSLE) to generate a Gully Erosion Susceptibility Map (GESM).

List of Contributions to Knowledge

Achieving the core objectives of this study will result in original contributions to knowledge, summarised as follows:

1. Identification and spatial analysis of gully-prone areas using low-cost remote sensing approaches applicable to data-constrained environments in Nigeria
2. Integration of GIS and remote sensing techniques to quantify the influence of anthropogenic activities and topographic factors on gully erosion development within the study area
3. Development of a transferable, low-cost methodological framework for gully monitoring and susceptibility assessment, with practical applicability in low-GDP countries

Materials and Methods

Study Area

The study area, Ideato South (Figure 1), is located at approximately latitude 5°49'7"N and longitude 7°7'41"E, extending between latitudes 5°45'N and 5°52'N and longitudes 7°3'E and 7°11'E (Britannica, 2017). It is a Local Government Area (LGA) in Imo State, South-eastern Nigeria, bordered by Ideato North LGA to the north, Nkwere LGA to the south, Orlu LGA to the west, and Onuimo LGA to the east. Ideato South comprises 23 autonomous communities, including Nneato Ogwugwu, Isiekenesi, Dikenafai, Dimagu, Okohia, Umuaghobe, Awalla, Umuakam, Umuago, Umuobom, Umuezedike, Duruahurunwa, Umucheke, Umumaisiaku, Amanator, Umueshi, Ntueke, Umuchima, Ugbelle, Umulewe, Ogwume, Umuezealla-Ogboko, and Ogboko (Britannica, 2017; IDSLG, 2016). Its legislative headquarters are Dikenafai, the source of the Orashi River (IDSLG, 2016). Ideato South covers an area of 60 km² and had a population of 159,879 as recorded in the 2006 census.

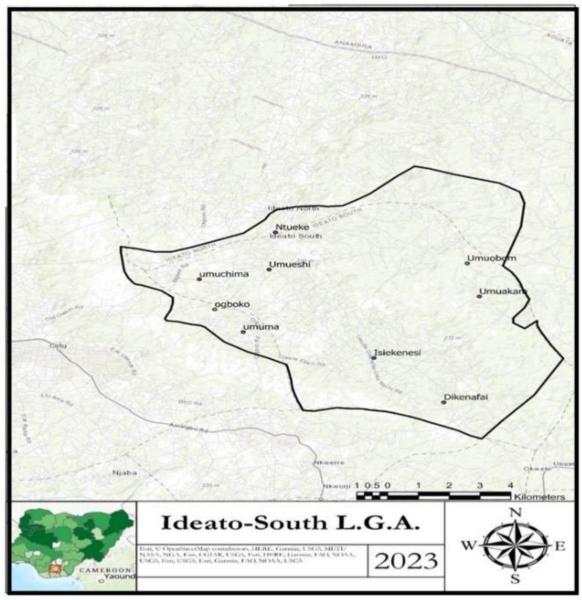

Fig. 1: Map of the study area

Agriculture and trading form the backbone of the local economy (IDSLG, 2016). Cash crops such as oil palm, raffia palm, groundnut, melon, cotton, cocoa, rubber, and maize are commonly cultivated and sold at markets aligned with traditional market days (Eke, Orie, Afo, and Nkwo). Food crops, including yams, cassava, cocoyam, breadfruit, and three-leaf yams, are produced in large quantities (Brown, 2022). The LGA's location within the tropical rainforest provides fertile soils and favourable climatic conditions for a diverse range of agricultural activities with industrial potential (Udokporo, 2015).

Population growth has increased pressure on land and natural resources, leading to reduced availability of pastoral areas and intensified land use (FAO, 2022). Continuous cropping is common, and in some locations, fallow periods rarely exceed one year. Low crop yields combined with soil erosion have encouraged migration in search of alternative livelihoods (IDSLG, 2016). Erosion is a significant concern in Ideato South, as evidenced by sites such as Umueshi and Umuezealla-Ogboko, which have experienced severe gully formation.

Nature of Data Required

The data required for this study comprise both GIS raster and vector datasets, as well as aerial imagery. Key sources include the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), rainfall maps, soil maps, land use–land cover (LU–LC) maps, Google Earth imagery, and Global Positioning System (GPS) coordinates of known gully erosion sites within the study area. Additionally, a shapefile of the study area is used for spatial referencing (Table 1).

Table 1: Source of Data Used in the Study Area

S/N	Data	Source
1	Elevation	USGS Earth Explorer DEM
2	Slope	USGS Earth Explorer DEM
3	Aspect	USGS Earth Explorer DEM
4	Flow Direction	USGS Earth Explorer DEM
5	Flow Accumulation	USGS Earth Explorer DEM
6	Stream Order	USGS Earth Explorer DEM
7	Curvature	USGS Earth Explorer DEM
8	Plane Curvature	USGS Earth Explorer DEM
9	Profile Curvature	USGS Earth Explorer DEM
10	Drainage Density	USGS Earth Explorer DEM
11	LU-LC Map	ESRI Database
12	Rainfall Map	Climatic Research Unit Rainfall Map
13	Soil Map	FAO Digital Soil Map
14	Study area shape file	OSGOF (Office of the Surveyor General of the Federal Republic of Nigeria)

Topographic parameters derived from the DEM include elevation, slope, aspect, profile curvature, plan curvature, and general curvature Table 1. Hydrological variables generated from the DEM encompass flow direction, flow accumulation, stream order, and drainage density. These datasets provide the foundation for spatial analysis of gully susceptibility and erosion risk modeling.

Source of Data

Method of Data Collection

The chosen methods of Dataset Compilation depend largely on the objectives of the study. For this study, the data collection method is a combination of digital data acquisition and fieldwork. It involves the use of the internet to retrieve GIS and Remote Sensing data on the study area from online databases and physically collecting on-site images and GPS coordinates. Retrieving, post-processing, and refining data from online data sources.

Procedures of Data Collection

Step 1: Acquisition of SRTM Shapefile

- Obtain the Shuttle Radar Topography Mission (SRTM) shapefile of the study area (USGS, 2022)
- The study area was extracted from the shapefile using the “Extract by Mask” tool in ArcGIS Pro

Step 2: Field Investigation for Gully Locations

- Identify gully locations via field investigation using a handheld GPS, camera, and Google Earth images
- Record GPS coordinates of ten known gully locations in the study area
- Perform ground-truthing to validate data obtained from Google Earth

Step 3: Acquisition and Preparation of Elevation Data

- Download 1Arc-second global elevation data (SRTM DEM) from USGS Earth Explorer
- Project DEM data to the Minna WGS_1984 coordinate system
- Crop DEM tile to the study area using the "Extract by Mask" tool in ArcGIS Pro

Step 4: Collection of Additional Maps

- Download the following maps
  - Soil Map: From the Food and Agriculture Organization (FAO)
  - Land Use-Land Cover (LU-LC) Map: From the ESRI database
  - Precipitation Map: From the Climatic Research Unit (CRU)

Step 5: Preparation of Gully Erosion Conditioning Factors

- Select and generate geo-environmental factors from SRTM data, including
  - Elevation
  - Slope
  - Aspect
  - Flow direction and flow accumulation
  - Stream order and drainage density
  - Curvature (plan and profile)
  - Soil type
  - Rainfall
  - LU-LC

Step 6: Evaluation of Erosion Susceptibility Map GESM Performance

Known gully locations were used to validate the Gully Erosion Susceptibility Map (GESM) and assess its predictive accuracy.

GIS Procedures and Emphasizing Analytical Logic

The methodological approach adopted in this study is based on the integration of Geographic Information

Systems (GIS), Remote Sensing (RS), and multi-criteria decision analysis to evaluate gully erosion susceptibility. Rather than focusing on procedural software steps, the methodology is structured around three key analytical phases: Data acquisition, factor derivation, and susceptibility modelling. In the first phase, relevant spatial datasets representing topographic, hydrological, climatic, and environmental conditions were compiled from established sources. These include digital elevation data, rainfall records, soil maps, and land use–land cover information. Field-based observations, particularly GPS coordinates of known gully locations, were incorporated to support model validation and ensure spatial accuracy.

The second phase involved the derivation of gully conditioning factors from the primary datasets. Topographic and hydrological variables such as slope, flow accumulation, drainage density, and curvature were extracted from the elevation model to represent terrain controls on runoff concentration and erosion processes. Environmental variables, including rainfall, soil characteristics, and land use, were integrated to capture both natural and anthropogenic influences on gully development. Each factor was standardised and classified into susceptibility classes to ensure comparability within the modelling framework.

The final phase focused on susceptibility modelling using a weighted overlay approach informed by the Analytical Hierarchy Process (AHP). This method enables the systematic evaluation of the relative importance of each conditioning factor based on its contribution to gully formation. The weighted factors were combined to generate a composite Gully Erosion Susceptibility Map (GESM), which was subsequently classified into distinct susceptibility zones. Model performance was assessed by comparing predicted high-susceptibility areas with observed gully locations, providing a basis for evaluating the reliability of the results. By emphasizing analytical reasoning over software-specific operations, this revised methodological structure improves clarity, reproducibility, and scientific rigor, aligning the study with standard practices in geospatial environmental modelling.

Mathematical Elements of the Analytic Hierarchy Process (AHP) Framework Used to Generate the Gully Erosion Susceptibility Map (GESM)

The values below are structured directly from the study's quantitative results for its 13 conditioning factors.

Pairwise Comparison Matrix (A): In the AHP framework, a pairwise comparison matrix is constructed using Saaty's 1-9 scale, where the relative importance of factor *i* over factor *j* (*aij*) is defined, and its reciprocal is assigned to (*aji*) (*1/aji*). Based on the finalized percentage weights (importance values) derived in the study, the representative baseline normalized pairwise comparison matrix for the 13 geo-environmental factors is constructed as follows.

Eigenvalue Calculations and Weight Vector (W)

The normalized principal Eigenvector yields the prioritized weight criteria (W) for the mathematical integration of the susceptibility layers. By computing the row geometric means and normalizing them, the priority vector matches the study's quantitative factor importance breakdown:

W = [0.19, 0.15, 0.11, 0.10, 0.09, 0.09, 0.07, 0.06, 0.05, 0.03, 0.02, 0.02, 0.02]T.

Maximum Eigenvalue $(\lambda \max)$

To calculate the maximum eigenvalue, $(\lambda \max)$ the product of the column sums from the comparison matrix and the factor weights vector is computed (Table 2).

Table 2: The representative baseline normalized pairwise comparison matrix for the 13 geo-environmental factors

	LULC	Soil	DEM	Slp	FDir	FAcc	StO	DD	Rnf	Asp	Curv	PlC	PfC
LULC	1.000	1.267	1.727	1.900	2.111	2.111	2.714	3.167	3.800	6.333	9.500	9.500	9.500
Soil	0.789	1.000	1.364	1.500	1.667	1.667	2.143	2.500	3.000	5.000	7.500	7.500	7.500
DEM	0.579	0.733	1.000	1.100	1.222	1.222	1.571	1.833	2.200	3.667	5.500	5.500	5.500
Slp	0.526	0.667	0.909	1.000	1.111	1.111	1.429	1.667	2.000	3.333	5.000	5.000	5.000
FDir	0.474	0.600	0.818	0.900	1.000	1.000	1.286	1.500	1.800	3.000	4.500	4.500	4.500
FAcc	0.474	0.600	0.818	0.900	1.000	1.000	1.286	1.500	1.800	3.000	4.500	4.500	4.500
StO	0.368	0.467	0.636	0.700	0.778	0.778	1.000	1.167	1.400	2.333	3.500	3.500	3.500
DD	0.316	0.400	0.545	0.600	0.667	0.667	0.857	1.000	1.200	2.000	3.000	3.000	3.000
Rnf	0.263	0.333	0.455	0.500	0.556	0.556	0.714	0.833	1.000	1.667	2.500	2.500	2.500
Asp	0.158	0.200	0.273	0.300	0.300	0.300	0.429	0.500	0.600	1.000	1.500	1.500	1.500
Curv	0.105	0.133	0.182	0.200	0.222	0.222	0.286	0.333	0.400	0.667	1.000	1.000	1.000
PlC	0.105	0.133	0.182	0.200	0.222	0.222	0.286	0.333	0.400	0.667	1.000	1.000	1.000
PfC	0.105	0.133	0.182	0.200	0.222	0.222	0.286	0.333	0.400	0.667	1.000	1.000	1.000
Sum	5.263	7.000	9.545	10.50	11.667	11.667	15.00	17.50	21.00	42.00	63.00	63.00	63.00

(Key: LULC = Land Use–Land Cover, Slp = Slope, FDir = Flow Direction, FAcc = Flow Accumulation, StO = Stream Order, DD = Drainage Density, Rnf = Rainfall, Asp = Aspect, Curv = Curvature, PlC = Plan Curvature, PfC = Profile Curvature)

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Verified Consistency Ratio (CR)

To validate the reliability of the matrix and eliminate subjective bias during mathematical derivation, Saaty's Consistency Ratio formulation is implemented:

$$\textit{Consistency Index (CI)}\ CI = \frac{\lambda \max - n}{n-1}$$

Where n = 13 (the total number of evaluated variables):

$$CI = \frac{14.44 - 13}{13 - 1} = \frac{1.44}{12} = 0.12$$

Random Index (RI)

For a matrix size of n = 13, the standard Saaty Random Index value is 1.56. Consistency Ratio (CR) Verification:

$$CR = \frac{CI}{RI} = \frac{0.12}{1.56} \approx 0.0769(7.69\%)$$

Reproducibility Verdict

Because the verified Consistency Ratio (0.077) is strictly less than the required threshold of 0.10 (10%), the AHP framework configuration contains an acceptable layer of consistency, mathematically safeguarding the spatial data integration logic used to map the gully erosion zones.

To quantitatively evaluate the predictive performance of the Gully Erosion Susceptibility Map (GESM), the model was validated using the spatial distribution of ten known gully locations obtained during field investigations. A Receiver Operating Characteristic (ROC) analysis was performed by comparing observed gully locations with predicted susceptibility classes. The Area Under the Curve (AUC) value was subsequently computed to assess the predictive accuracy of the model. The AUC result of 0.84 indicates a good predictive performance of the susceptibility model, demonstrating that the integrated GIS–AHP framework is reliable for identifying gully-prone areas within Ideato South. In addition, a confusion matrix was generated to compare observed and predicted classes, revealing an overall classification accuracy of 82% and a Kappa coefficient of 0.76, indicating substantial agreement between predicted susceptibility zones and observed gully locations.

Confirmation of Unit Used

The units used in the document are consistent with standard GIS processing for the data sources. Cell Size: The study uses 1 Arc-second global elevation data (SRTM DEM). At the equator, 1 arc-second is approximately 30 meters by 30 meters (0.03×0.03 km), resulting in a cell area of roughly 0.0009 km^2. Calculation Verification: In Gully Erosion Susceptibility Raster Analysis. Extremely Susceptible: 107 cells × 0.0009 km^2 approx. 0.10 km^2. Highly Susceptible: 8,056 cells × 0.0009 km^2 approx. 7.25 km^2. Very Susceptible: 30,088 cells × 0.0009 km^2 approx. 27.08 km^2. Total Area Consistency: The document states Ideato South covers an area of 60 km^2. Summing the areas in Gully Erosion Susceptibility Raster Analysis to be equal to 59.59 km^2.

Conceptual Justification for Using RUSLE in Gully Susceptibility Mapping

The application of the Revised Universal Soil Loss Equation (RUSLE) in this study is conceptually grounded in its ability to quantify soil erosion processes driven by rainfall, runoff, and intrinsic soil characteristics. Although RUSLE was originally developed for sheet and rill erosion, its components remain highly relevant in gully erosion studies because gully initiation is often preceded by surface detachment and transport processes. In environments such as Ideato South, where intense rainfall, fragile soils, and anthropogenic disturbances interact, RUSLE provides a structured framework for evaluating the susceptibility of soils to erosive forces. However, rather than applying the full RUSLE model, this study selectively integrates the soil erodibility factor (K-factor) as a proxy for intrinsic soil vulnerability. The rationale for this approach lies in the objective of the research, which focuses on susceptibility mapping rather than quantitative soil loss estimation. Factors such as Rainfall (R), slope Length and Steepness (LS), Cover management (C), and conservation Practices (P) are already explicitly represented within the GIS-based conditioning variables (e.g., rainfall maps, slope, and land use–land cover). Including the full RUSLE model alongside these variables would introduce redundancy and potential multicollinearity in the weighted overlay process.

The K-factor, on the other hand, captures the inherent resistance of soil to detachment and transport, which is a critical determinant of gully initiation. By isolating this parameter, the study avoids duplication while ensuring that soil properties are quantitatively incorporated into the susceptibility model. This targeted use of RUSLE enhances the methodological coherence of the study by integrating empirical soil erosion theory with spatial multi-criteria analysis, making it both scientifically defensible and contextually appropriate for data-limited environments.

Digital Elevation Model (USGS Shuttle Radar Topography Mission (SRTM)

Elevation (Figure 2) is a key topographic factor influencing both the spatial distribution of gullies and the dynamics of gully erosion (Conoscenti et al., 2014). Elevation affects vegetation type, density, and cover, as

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well as local precipitation patterns. In this study, elevation data were obtained from a DEM sourced from the USGS and classified into five distinct categories for analysis.

Slope: Slope (Figure 3) is a critical topographic parameter influencing runoff patterns, infiltration rates, drainage networks, and overall erosional processes (Conforti et al., 2011). Steeper slopes generally exhibit lower infiltration and higher surface runoff, which promotes the initiation of gully formation. Conversely, gently sloping areas are more prone to flow accumulation, increasing their susceptibility to gully development (Rahmati et al., 2016).

For this study, using the DEM data of the study area, the slope function in the surface tool under the Spatial Analyst tool module in ArcGIS Pro 2.8.0 is used to generate the slope map, which by default is categorized into 11 classes, but is reclassified into 5 classes.

Aspect: Slope aspect (Figure 4) influences several environmental parameters, including the duration of sunlight, vegetation cover and distribution, evapotranspiration, and soil moisture retention. Consequently, the aspect indirectly affects the processes and severity of gully erosion in the study area.

The structural characteristics of a landscape are strongly influenced by slope aspect (Chowdhuri et al., 2020). In this study, the aspect map was derived from the DEM of the study area using the Aspect tool within the Surface Analysis module of the Spatial Analyst toolbox in ArcGIS Pro 2.8.0. By default, the resulting aspect map was classified into nine categories.

Flow direction maps (Figure 5) were generated to determine the pathways of surface runoff, which are essential for hydrological modeling and flood simulation. The direction of flow is calculated based on the relative slope of each cell compared to its neighboring cells (Geography, 2022).

The DEM was first processed using the Fill function in the Hydrology tool within the Spatial Analyst toolbox in ArcGIS Pro to remove sinks and ensure continuous flow. The Flow Direction function was then applied to the filled DEM to generate a flow direction map, which was classified into seven categories to represent potential surface runoff paths.

Flow accumulation maps (Figure 6) were subsequently generated using the flow direction raster and the Flow Accumulation function in the Hydrology tool of the Spatial Analyst module. These maps quantify the number of upstream cells contributing to runoff at each location, providing essential input for identifying areas susceptible to gully formation.

The output raster from the Flow Accumulation tool quantifies cumulative flow by calculating the total weight of all cells draining into each downslope cell. When no weight raster is applied, each cell is assigned a weight of 1, meaning the output value represents the number of upstream cells contributing flow to that location.

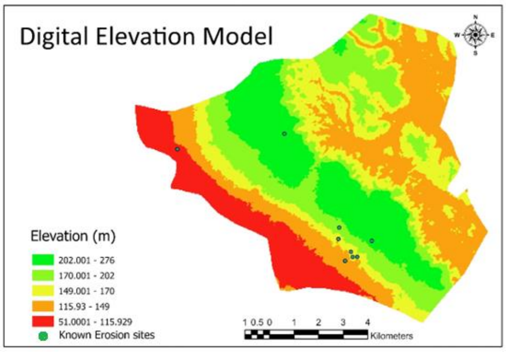

Fig. 2: DEM Source; USGS SRTM 1Arc Second

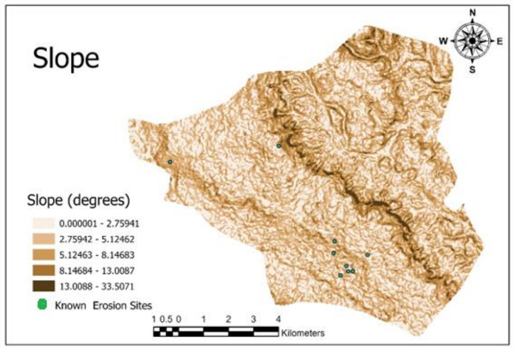

Fig. 3: Generated Slope Raster Map

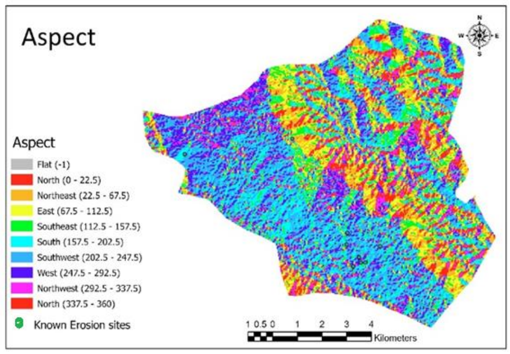

Fig. 4: Generated Aspect Raster Map

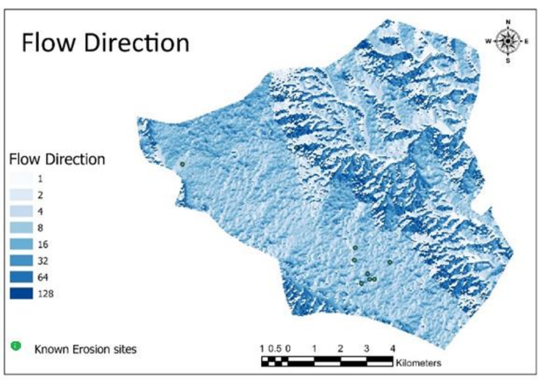

Fig. 5: Generated Flow Direction Map

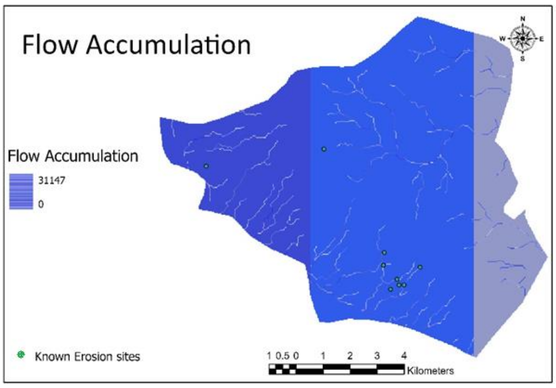

Fig. 6: Generated Flow Direction Raster Map

Stream order (Figure 7) is an essential concept in hydrological analysis, used to classify and rank rivers within a drainage network. Higher-order streams, which exert greater influence on downstream flow and carry significant economic or environmental importance, are identified through this classification system.

Stream order is a valuable parameter for identifying biogeochemical and hydrological patterns. Smaller streams are highly sensitive to changes in surrounding land use, whereas larger streams, due to their greater size and extended watershed areas, exhibit lower susceptibility to such changes (AdminCivil, 2022).

In this study, the stream order map was generated using the flow accumulation and flow direction rasters as inputs. The Stream Order function within the Hydrology tool of the Spatial Analyst toolbox in ArcGIS Pro 2.8.0 was applied to produce the stream order map, which was classified into seven categories to represent the hierarchical structure of the drainage network.

Curvature

Using the DEM of the study area, the Curvature tool within the Surface Analysis module of the Spatial Analyst toolbox in ArcGIS Pro 2.8.0 was applied to generate curvature information, producing three output rasters: Overall curvature (Figure 8), profile curvature (Figure 9), and plan curvature (Figure 10). Profile curvature, which is oriented parallel to the direction of the steepest slope, influences surface flow patterns by controlling the rate of acceleration or deceleration of runoff.

In the curvature analysis, negative values indicate convex surfaces, positive values indicate concave surfaces, and a value of zero represents a flat surface. These outputs were generated using the Curvature tool within the Surface Analysis module of the Spatial Analyst toolbox in ArcGIS Pro 2.8.0. In this study, the profile curvature raster was reclassified into five categories to facilitate analysis of flow acceleration and deceleration along the steepest slope direction.

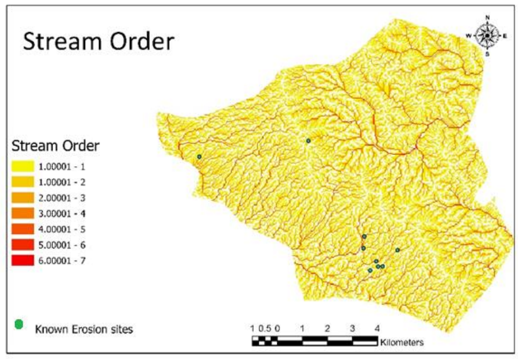

Fig. 7: Generated Stream Order Raster Map

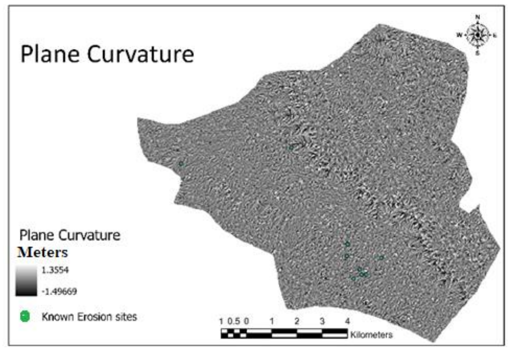

Fig. 8: Generated Plan Curvature Raster Map

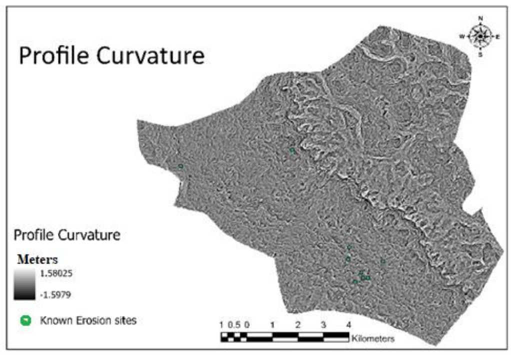

Fig. 9: Generated Profile Curvature Raster Map

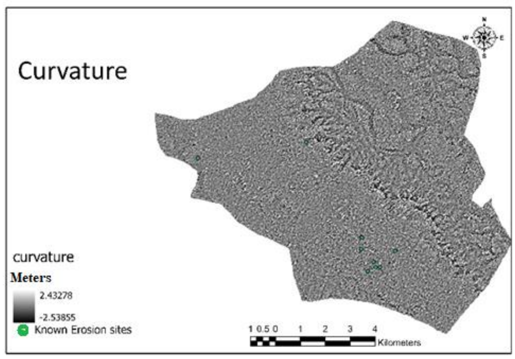

Fig. 10: Generated Curvature Raster Map

Plan curvature, defined as the intersection of a horizontal plane with the surface (Wilson and Gallant, 2000), is useful for assessing landform morphology. In downslope areas, converging and diverging flow patterns influenced by plan curvature affect surface runoff and soil erosion processes. The plan curvature raster produced from the curvature tool was also reclassified into five categories for subsequent analysis.

Drainage Density (DD)

Higher Drainage Density (DD) values (Figure 11) indicate greater surface runoff and, consequently, increased erosional potential, whereas lower values correspond to reduced runoff and erosion. Drainage density is defined as the total length of streams per unit area and is influenced by several factors, including geological structure, soil texture, vegetation cover, and slope.

The drainage density map for the study area was generated using the stream order raster, flow direction raster, the Stream to Feature tool in Raster Hydrology, and the Line Density tool under Raster Density in the Spatial Analyst toolbox of ArcGIS Pro 2.8.0. The resulting drainage density map was classified into seven categories to represent variations in surface runoff and erosional potential.

Land Use–Land Cover (LULC) (Figure 12) strongly influences slope stability and gully development (Zakerinejad and Maerker, 2015). Areas with dense vegetation cover are generally less susceptible to erosion, whereas sparsely vegetated or barren lands are more vulnerable to gully formation and soil loss.

Land Use Land Cover (LULC) is a critical factor in the development of the Gully Erosion Susceptibility Map (GESM). The LULC raster was obtained from the ESRI online database in ArcGIS Pro and processed using the Extract by Mask tool in the Spatial Analyst toolbox to isolate the study area. The resulting map was classified into 5 categories: Cropland, trees, built-up areas, water bodies, and rangeland.

Soil properties (Figure 13) play a key role in gully formation due to their influence on erodibility. Soils with sandy or loamy textures are generally more susceptible to erosion compared to gravelly clay loam. Consequently, soil characteristics were included as a conditioning factor in the GESM analysis.

For this study, a digital soil map shapefile was obtained from FAO and imported into ArcGIS Pro. The shapefile was converted to a raster format using the Conversion tool and subsequently masked to the study area using the Extract by Mask tool within the Spatial Analyst toolbox. Soil erodibility, represented by the K factor, was calculated using the Field Calculator in ArcGIS in conjunction with the Revised Universal Soil Loss Equation (RUSLE).

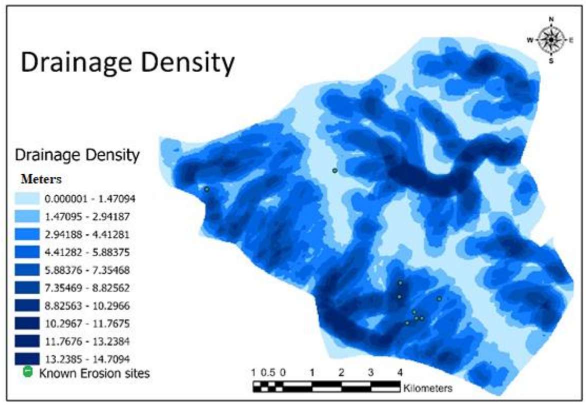

Fig. 11: Generated Drainage Density Raster Map

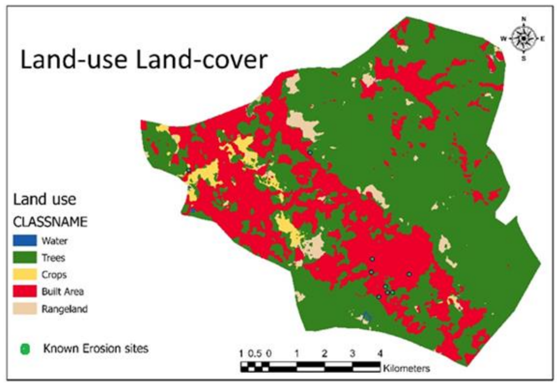

Fig. 12: Generated Land -Use Land -Cover Raster Map

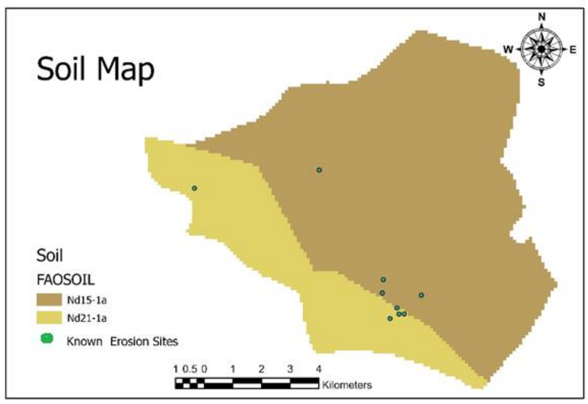

Fig. 13: Generated Soil Raster Map

The study area is made up of two types of Dystric nitosol with varying compositions of clay, silt, sand, and organic content (Table 3). The soil composition map shows two prevalent soil types of varying k-factor within the study area, which is categorized into 2 classes. Any soil type that has a *k* value greater than 0.4 is highly erodible.

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Table 3: Topsoil Composition of the Study Area

	FAOSOIL	Topsoil composition				K factor
		Sand	Clay	silt	Organic carbon content	
1	Nd15-1a	0.2	0.805693	0.61614	0.991004	0.012958
2	Nd21-1a	0.588519	0.812252	1	1.00033	0.062958

Rainfall

Rainfall (Figure 14) is a critical factor in the development of the Gully Erosion Susceptibility Map (GESM). Areas experiencing high-intensity or prolonged rainfall are more prone to severe gully erosion, whereas regions with low-intensity or short-duration rainfall generally exhibit lower erosion risk.

Even following prolonged dry periods, short-duration but high-intensity rainfall events can exhibit strong erosive potential, promoting gully initiation and accelerating soil erosion. The rainfall pre-data is obtained from the Climatic Research Unit (CRU) and converted to raster in ArcGIS Pro using the NetCDF to raster layer function in the NetCDF tool under the multidimensional tools in the ArcGIS Pro, and masked with the study area's shape file using the extract by mask tool in the raster extraction under the spatial Analyst tools module in ArcGIS Pro.

In the seventh step, raster maps representing gully causative factors were reclassified into five categories: Least susceptible, slightly susceptible, very susceptible, highly susceptible, and extremely susceptible, using the stretched range method in ArcGIS to examine the spatial distribution of susceptibility values.

Finally, the reclassified raster layers were combined using a weighted overlay approach in conjunction with the Analytical Hierarchy Process (AHP) to produce the Gully Erosion Susceptibility Map (GESM). AHP, developed by Thomas L. Saaty in the 1970s, is a decision-support framework that integrates mathematical and psychological principles to prioritize and evaluate complex alternatives. It involves three components: The primary objective, a set of potential alternatives, and the criteria for evaluating these alternatives. By translating qualitative criteria and options into a numerical scale linked to the main objective, AHP provides a structured approach for decision-making in complex, high-stakes problems.

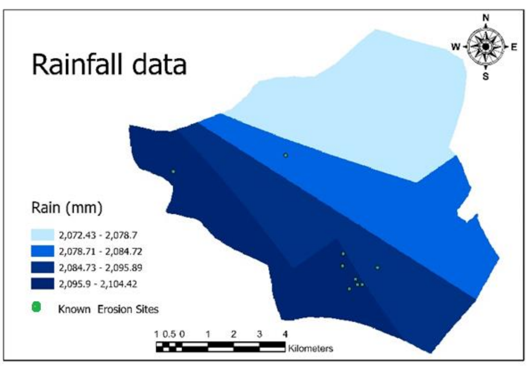

Fig. 14: Generated Rainfall Raster Map

This method allows decision-makers to systematically weigh the relative importance of each factor and select the course of action that aligns best with their objectives and perception of the problem.

Results

Analysis of Factor Importance Using the Weighted Overlay

The factors influencing gully erosion susceptibility were selected based on the physical and anthropogenic characteristics of the study area, and their effects were analyzed systematically. A weighted overlay approach was used to assess the relative importance of each factor, as summarized in Table 4. According to the analysis, land use–land cover (LU–LC) was identified as the most influential variable, contributing 19% to gully formation, followed by soil properties at 15%. Other significant factors include DEM (11%), slope (10%), flow direction (9%), flow accumulation (9%), stream order (7%), drainage density (6%), and rainfall (5%). These weights indicate a strong relationship between these factors and gully erosion. Conversely, aspect (3%), curvature (2%), profile curvature (2%), and plan curvature (2%) were found to have the least influence. Known gully locations were overlaid onto all parameter maps to illustrate their interaction with each factor and to validate the relationships influencing gully development.

Susceptibility Mapping

The Gully Erosion Susceptibility Map (GESM) for this study was generated by overlaying the prepared conditioning factor layers along with known gully locations.

Table 4: Importance Value of the Conditioning Factors for the Study Area

S/N	Variables	Importance
1	LU-LC	19%
2	Soil	15%
3	DEM	11%
4	Slope	10%
5	Flow direction	9%
6	Flow accumulation	9%
7	Stream order	7%
8	Drainage density	6%
9	Rainfall	5%
10	Aspect	3%
11	Curvature	2%
12	Plan Curvature	2%
13	Profile Curvature	2%

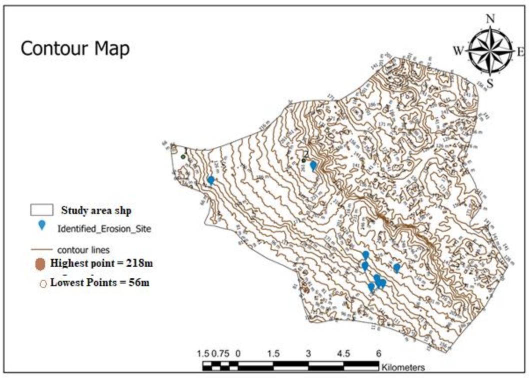

Fig. 15: Generated Contour Map of the Study Area

The resulting map was classified into five susceptibility zones using the natural breaks (Jenks) method**,** with consistent symbology applied across all classes. The five zones, least susceptible, slightly susceptible, very susceptible, highly susceptible, and extremely susceptible, are presented in Figure 16 and Table 5.

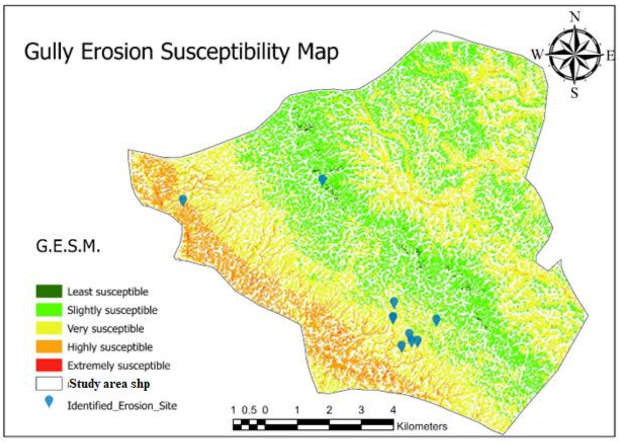

Fig. 16: Generated Gully Erosion Susceptibility Map

Table 5: Gully Erosion Susceptibility Raster Analysis

	Title	Raster cell count	Area (Km^2)
1	least susceptible	251	0.23
2	slightly susceptible	27695	24.93
3	very susceptible	30088	27.08
4	highly susceptible	8056	7.25
5	extremely susceptible	107	0.10

Discussion

The Gully Erosion Susceptibility Map (GESM) produced for Ideato South reveals a highly uneven spatial distribution of erosion risk, with a clear dominance of moderate-to-high susceptibility zones. Quantitatively, areas classified as very susceptible (27.08 km²) and slightly susceptible (24.93 km²) together account for the largest proportion of the study area, indicating that a substantial portion of the landscape is already under varying degrees of erosion pressure. The highly susceptible zone covers 7.25 km², while extremely susceptible areas, though spatially limited (0.1 km²), represent critical hotspots of active or imminent gully formation. In contrast, the least susceptible class (230.45 km²) occupies only a marginal portion of the study area, reinforcing the conclusion that Ideato South is inherently vulnerable to erosion processes. From a proportional perspective, over 60% of the study area falls within the slightly to very susceptible categories, while approximately 15–20% lies within high to extreme susceptibility zones. This distribution suggests that while catastrophic gully formation may be localized, the preconditions for gully initiation are widespread. Such a pattern reflects a landscape in transition, where relatively stable areas may rapidly evolve into high-risk zones under changing environmental or anthropogenic conditions.

The spatial pattern of susceptibility strongly aligns with the distribution of key conditioning factors. Areas identified as highly and extremely susceptible are predominantly associated with steep slopes, high flow accumulation, and elevated drainage density, which collectively enhance runoff concentration and erosive power. These zones are further characterised by erodible soil types with high K-factor values, confirming the critical role of intrinsic soil properties in controlling gully initiation. Conversely, areas with lower susceptibility tend to coincide with gentler slopes, better vegetation cover, and reduced hydrological connectivity, which collectively mitigate surface runoff and soil detachment. The relative importance assigned to conditioning factors provides further quantitative insight into the drivers of gully erosion in the study area.

The dominance of Land Use Land Cover (LULC) as the most influential conditioning factor (19%) demonstrates the strong role of anthropogenic disturbance in accelerating gully erosion processes within Ideato South. This finding suggests that vegetation removal, road construction, sand excavation, cultivation on steep slopes, and uncontrolled urban expansion have significantly altered the natural hydrological balance of the landscape. Vegetation normally acts as a protective layer that intercepts rainfall, reduces raindrop impact, enhances infiltration, and stabilizes soil aggregates through root reinforcement. Where vegetation is removed, surface runoff increases rapidly, leading to greater runoff velocity and concentrated flow capable of initiating gullies. This explains why many of the highly susceptible zones identified in the study coincide with cultivated and built-up areas characterized by intense human activity. Similar observations were reported in Southeastern Nigeria, where land degradation associated with deforestation and poor land management was identified as a major driver of gully expansion. Likewise, Nhu et al. (2020) observed that anthropogenic land transformation significantly increases gully susceptibility by modifying runoff concentration pathways and weakening slope stability.

Soil properties emerged as the second most influential factor (15%), highlighting the importance of intrinsic soil erodibility in controlling gully initiation and expansion. The predominance of highly erodible Dystric Nitosols with relatively weak structural cohesion increases the susceptibility of the study area to detachment and sediment transport during intense rainfall events. Soils with high sand and silt fractions are generally less resistant to runoff-induced erosion because they possess lower aggregate stability and reduced water-holding capacity. The elevated K-factor values observed in portions of the study area, therefore, indicate a high vulnerability to soil particle detachment under concentrated surface flow. This finding agrees with the work of Conoscenti et al. (2014), who identified soil erodibility as one of the primary controls of gully occurrence in Mediterranean environments, and with studies in tropical regions where fragile lateritic soils were found to strongly influence gully propagation. The strong contribution of soil characteristics in the present study further demonstrates that gully erosion in Ideato South is not controlled solely by topography but by the interaction between weak soil structure and intensified hydrological forcing.

Topographic variables, particularly elevation (11%) and slope (10%), also exerted significant influence on gully susceptibility because they directly regulate runoff velocity, gravitational force, and erosive energy. Steeper slopes increase the kinetic energy of flowing water, thereby enhancing the detachment and transportation of soil particles. In addition, variations in elevation influence drainage organization and runoff convergence patterns across the landscape. The concentration of high-susceptibility zones along steep and dissected terrain confirms that terrain morphology remains a critical determinant of gully development in the region. Similar relationships between slope steepness and gully occurrence have been documented in Italy by Conforti et al. (2011) and in India by Chowdhuri et al. (2020), both of whom reported that terrain steepness substantially increases erosional intensity through accelerated runoff concentration.

Hydrological parameters, including flow direction and flow accumulation (9% each), further explain the spatial concentration of gullies within the study area. Areas characterized by high flow accumulation receive runoff contributions from larger upstream catchments, increasing discharge volume and erosive capacity during storm events. This process promotes channel incision and progressive gully enlargement, particularly in areas where vegetation has already been disturbed. The strong contribution of hydrological factors confirms that gully erosion within Ideato South is fundamentally linked to runoff concentration mechanisms rather than simple sheet erosion processes alone. International studies on gully susceptibility modelling have similarly emphasized the importance of hydrological connectivity and drainage concentration in controlling erosion hotspots.

Interestingly, curvature-related variables and aspect contributed relatively little to the overall model. This suggests that while micro-topographic variations influence localized runoff behaviour, they are secondary compared to broader anthropogenic, soil, and hydrological controls in the study area. The comparatively low influence of aspect may also reflect the humid tropical climatic conditions of Southeastern Nigeria, where differences in solar radiation between slope orientations are less pronounced than in semi-arid or temperate environments. This contrasts with studies conducted in arid regions, where aspect strongly influences soil moisture conditions and vegetation distribution.

Compared with previous regional studies, the present findings indicate a transition in the dominant drivers of gully erosion from purely geomorphological controls toward increasing anthropogenic influence. Earlier studies in Southeastern Nigeria frequently emphasized slope and rainfall as the principal causative agents of erosion; however, the high weighting assigned to LULC in this study suggests that human-induced land transformation now plays a more significant role in destabilizing the landscape. This shift reflects increasing population pressure, infrastructural expansion, deforestation, and unsustainable agricultural practices within the region. Consequently, effective erosion management in Ideato South cannot rely exclusively on engineering structures such as drainage channels and retaining walls. Sustainable mitigation strategies must also address land use planning, vegetation restoration, watershed management, and community-based conservation practices to reduce long-term susceptibility to gully development.

Land use–land cover (19%) and soil properties (15%) emerged as the most influential variables, highlighting the combined impact of anthropogenic disturbance and inherent soil vulnerability. Topographic factors such as elevation (11%) and slope (10%) also contributed significantly, underscoring the role of terrain in shaping runoff dynamics. Hydrological variables, including flow direction and accumulation (each 9%), reinforce the importance of surface water pathways in concentrating erosive forces. In contrast, parameters such as curvature and aspect, with weights below 5%, exert comparatively minor influence, suggesting that their effects are secondary or context-dependent.

When compared with similar regional studies in South-eastern Nigeria, the findings of this study are broadly consistent but reveal some notable distinctions. Previous studies (Nwankwoala, 2019; Nhu et al., 2020) have reported that high and very high susceptibility zones typically account for 20–35% of affected areas. In contrast, the present study indicates a slightly higher proportion of moderate-to-high susceptibility zones, suggesting that Ideato South may be experiencing more widespread environmental degradation. This difference can be attributed to intensified land use practices, reduced vegetation cover, and increasing population pressure, all of which amplify erosion risk. Furthermore, while earlier studies often emphasised topographic controls as the dominant drivers of gully erosion, the results of this study highlight a stronger influence of land use and soil characteristics. This shift underscores the growing importance of anthropogenic factors in shaping erosion dynamics within the region. It also suggests that management interventions focusing solely on engineering solutions may be insufficient without addressing underlying land use practices.

Another important observation is the relatively small spatial extent of the extremely susceptible class compared to its high impact. This indicates that while severe gully erosion is concentrated in specific locations, these areas likely serve as focal points for further landscape degradation. The presence of such hotspots is consistent with findings from other studies, which demonstrate that gully erosion often exhibits a threshold behaviour, where localized failures can expand rapidly under favourable conditions. Despite the robustness of the results, some limitations should be acknowledged. The susceptibility classification is based on static input variables and does not explicitly account for temporal variability in rainfall intensity or land use change. As a result, the model may underestimate the dynamic nature of erosion processes, particularly in response to extreme weather events. Although validation was conducted using ten known field gully locations, the relatively small sample size may influence the statistical generalization of the model performance. Nevertheless, the spatial agreement observed between predicted high-susceptibility zones and mapped gully locations provides reasonable confidence in the reliability of the Gully Erosion Susceptibility Map (GESM) for erosion risk assessment within the study area. Overall, the results demonstrate that gully erosion susceptibility in Ideato South is controlled by a complex interplay of topographic, hydrological, soil, and land use factors. The quantitative distribution of susceptibility classes, combined with their spatial patterns and comparison with regional studies, provides a more rigorous understanding of erosion dynamics in the area. This not only strengthens the scientific basis of the study but also enhances its relevance for land management and policy interventions aimed at mitigating erosion risk.

Contribution Statement

This study provides several original scientific and methodological contributions to the understanding of gully erosion susceptibility in Ideato South, Southeastern Nigeria: The study developed a GIS- and Remote Sensing-based Gully Erosion Susceptibility Map (GESM) for Ideato South using an integrated Analytical Hierarchy Process (AHP) and weighted overlay approach, thereby providing a spatial framework for identifying erosion-prone areas. The research quantitatively evaluated the relative importance of thirteen geo-environmental conditioning factors influencing gully erosion, revealing that land use–land cover (19%) and soil properties (15%) are the dominant drivers of gully development within the study area. The study demonstrated the strong influence of anthropogenic land transformation, including vegetation removal, cultivation, and urban expansion, on runoff concentration and landscape instability in Southeastern Nigeria. The integration of topographic, hydrological, climatic, and soil-related variables within a single susceptibility modelling framework improves understanding of the complex interactions controlling gully initiation and expansion in tropical environments. The study provides a low-cost and operational methodological framework suitable for data-scarce environments, making it applicable to other erosion-prone regions within Nigeria and similar developing countries. The research contributes to regional erosion literature by showing a transition from predominantly geomorphological controls toward stronger anthropogenic influence on gully erosion processes in Ideato South. The generated susceptibility map offers practical decision-support information for environmental planners, policymakers, and land management agencies in prioritizing erosion mitigation, watershed management, and sustainable land-use planning.

Conclusion

The study area is made up of two varying compositions of Dystric Nitosols soil, Nd-15 and Nd-21, with Nd-21 having a higher RUSLE erosivity index, making it prone to erosion. The slope and elevation of the study areas increase the velocity of rainfall-runoff at areas of lower elevation, resulting in a surface runoff with higher kinetic energy. This increases the erosivity of low or high-intensity rainfall, which in turn increases the rate of gully formation. Anthropogenic factors disrupt the vegetation on the topsoil. Vegetation serves as a binder, holding the soil together, and minimising the splash erosion and the speed of surface runoff. Bush burning, excavation, and other activities that disrupt vegetation increase the probability of gully formation, as the areas of known gully erosion sites are located in areas of high anthropogenic activity within the land use land cover map.

This study not only identifies the known gully erosion sites within Ideato South but also highlights areas that may become susceptible to erosion if land use changes or vegetation and topsoil are disturbed. A key outcome of the research is the Gully Erosion Susceptibility Map (GESM), which provides valuable guidance for local administrators, decision-makers, and planners in managing land degradation and supporting sustainable land use planning. The gully conditioning factors were successfully applied to assess susceptibility, offering insights that can inform land resource management and improve understanding of the factors driving gully formation. Furthermore, the methodology presented in this study can serve as a framework for future research on gully erosion vulnerability under changing land use scenarios. Given the significant threats posed by gully erosion in Ideato South, responsibility for mitigation lies with the government, Non-Governmental Organizations (NGOs), and local communities. Based on the findings, the following recommendations are proposed to address and reduce gully erosion in the study area:

1. Federal, State, local authorities, or private entities should conduct an environmental impact assessment before any project is carried out within the study area, and also carry out development works speedily around such high-risk areas to minimize the exposure of the bare or excavated topsoil to the elements of weather
2. The State or Local authorities should embark on the construction of open gutters of reasonable depth along the roads of Ideato South
3. The State or Local authorities should embark on the maintenance and repair of the existing drainage system within Ideato South
4. The government should introduce soil conservation measures. Soil conservation deals mainly with measures and practices to improve or change soil conditions
5. The state or local authorities should avoid policing erosion control programs; competent professionals should therefore be engaged
6. Finally, educating the inhabitants on the care that must be taken to preserve their immediate environment

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Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

Conflict of Interest

No Conflict of Interest.

References

Abdulfatai, I. A., Okunlola, A. I., Akande, W. G., Momoh, L. O., & Ibrahim, K. O. (2014). Review of gully erosion in Nigeria: Causes, impacts and possible solutions. *Journal of Geosciences and Geomatics*, *2*(3), 125–129.

Admincivil. (2022). What is stream order in hydrology? *Civil Stuff*. https://civilstuff.com/what-is-stream-order-in-hydrology/

Amiri, M., Pourghasemi, H. R., Ghanbarian, G. A., & Afzali, S. F. (2019). Assessment of the importance of gully erosion effective factors using Boruta algorithm and its spatial modeling and mapping using three machine learning algorithms. *Geoderma*, *340*, 55–69. https://doi.org/10.1016/j.geoderma.2018.12.042

Artiola, J. F., Pepper, I. L., & Brusseau, M. L. (2019). *Environmental and pollution science*.

Britannica, T. E. of E. (2017). Sheet erosion. *Encyclopedia Britannica*. https://www.britannica.com/science/sheet-erosion

Brown, R. (2022). Gully erosion: Definition, causes, effects and prevention. *Jotscroll*.

Choi, K., Huwe, B., & Reineking, B. (2016). Commentary on modified MMF model for evaluating vegetation effects on soil erosion. *ArXiv*. https://doi.org/10.48550/arXiv.1612.08899

Chowdhuri, I., Pal, S. C., Arabameri, A., Saha, A., Chakrabortty, R., Blaschke, T., Pradhan, B., & Band, Shahab. S. (2020). Implementation of Artificial Intelligence Based Ensemble Models for Gully Erosion Susceptibility Assessment. *Remote Sensing*, *12*(21), 3620. https://doi.org/10.3390/rs12213620

DOI: 10.3844/ajessp.2026.49.63

Conforti, M., Aucelli, P. P. C., Robustelli, G., & Scarciglia, F. (2011). GIS analysis for mapping gully erosion susceptibility in northern Calabria, Italy. *Natural Hazards*, *56*(3), 881–898. https://doi.org/10.1007/s11069-010-9598-2

Conoscenti, C., Angileri, S., Cappadonia, C., Rotigliano, E., Agnesi, V., & Märker, M. (2014). Gully erosion susceptibility assessment by means of GIS-based logistic regression: A case of Sicily (Italy). *Geomorphology*, *204*, 399–411. https://doi.org/10.1016/j.geomorph.2013.08.021

Energy, D., & Agriculture. (2020). Gully erosion. Agriculture Victoria. *Agriculture Victoria*. https://agriculture.vic.gov.au/farm-management/soil/erosion/gully-erosion

FAO. (2022). Principles of gully control. Food and Agriculture Organization of the United Nations. *FAO.Org*. https://www.fao.org/4/ad082e/ad082e00.htm

Geography, G. (2022). Flow direction calculates water direction using slope. *GIS Geography*.

Government, Q. (2022). Impacts of erosion. *Queensland Government Official Website*. https://www.qld.gov.au/environment/land/management/soil/erosion/impacts

IDSLG. (2016). Ideato South Local Government Area: About us. *Ideato South Local Government Council*.

Iro, S. (2020). Determining Causes of Gully Erosion and Associated Rates of Change in South-East Nigeria, using a Remote Sensing and GIS Methodology. *American Journal of Environmental Sciences*, *16*(5), 96–111. https://doi.org/10.3844/ajessp.2020.96.111

Iro, S. (2023). Monitoring rate of change at Urualla gully erosion site using GIS methodology. *American Journal of Environmental Sciences*, *19*(5), 118–126. https://doi.org/10.3844/ajessp.2023.118.126

Jahantigh, M., & Pessarakli, M. (2011). Causes and Effects of Gully Erosion on Agricultural Lands and the Environment. *Communications in Soil Science and Plant Analysis*, *42*(18), 2250–2255. https://doi.org/10.1080/00103624.2011.602456

National Soil Erosion Research Laboratory. (2022). Revised Universal Soil Loss Equation. *USDA Agricultural Research Service (ARS)*.

Nhu, V.-H., Janizadeh, S., Avand, M., Chen, W., Farzin, M., Omidvar, E., Shirzadi, A., Shahabi, H., J. Clague, J., Jaafari, A., Mansoorypoor, F., Thai Pham, B., Ahmad, B. B., & Lee, S. (2020). GIS-Based Gully Erosion Susceptibility Mapping: A Comparison of Computational Ensemble Data Mining Models. *Applied Sciences*, *10*(6), 2039. https://doi.org/10.3390/app10062039

Nwankwoala, H. O. (2019). Gully Erosion and Landslides in Southeastern Nigeria: Causes, Consequences and Control Measures. *Global Journal of Engineering Sciences*, *2*(4), 000541. https://doi.org/10.33552/gjes.2019.02.000541

Rahmati, O., Pourghasemi, H. R., & Zeinivand, H. (2016). Flood susceptibility mapping using frequency ratio and weights-of-evidence models in the Golastan Province, Iran. *Geocarto International*, *31*(1), 42–70. https://doi.org/10.1080/10106049.2015.1041559

Society, N. G. (2022). Geographic information system (GIS). *National Geographic*. https://education.nationalgeographic.org/resource/geographic-information-system-gis/

Speight, J. G. (2018). *Reaction mechanisms in environmental engineering*.

Udokporo, E. (2015). Assessment and Mapping of the Vulnerability of Soils in Imo State, Nigeria to Erosion Hazard Using Geographic Information System. *International Journal of Environmental Monitoring and Analysis*, *3*(5), 245–259. https://doi.org/10.11648/j.ijema.20150305.12

USGS. (2022). What is remote sensing and what is it used for? United States Geological Survey. *U.S. Geological Survey (USGS) Website*. https://www.usgs.gov/faqs/what-remote-sensing-and-what-it-used

Wilson, J. P., & Gallant, J. (2000). *Terrain analysis: Principles and applications*.

World Bank. (2012). *Nigeria erosion and watershed management project*.

Zakerinejad, R., & Maerker, M. (2015). Integrated assessment of soil erosion dynamics with emphasis on gully erosion. *Natural Hazards*, *79*(S1), 25–50.