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Gully Erosion Susceptibility Assessment and Mapping Using Integrated Geospatial Techniques and Multi-Criteria Decision Analysis for Selected Watersheds of Bale Highland, Oromia, Southeast Ethiopia

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Abstract

Gully erosion is one of the main causes of land degradation, which poses a serious threat to agricultural production, ecosystem stability, and the livelihoods of people living in the Ethiopian highlands. The objective of the study was therefore to analyze the spatial variability and relative importance of gully erosion conditioning factors and generate a map of gully erosion susceptibility to facilitate the selection of priority sub-watersheds for soil and water conservation works in the Bale Highlands. Different sources of spatial data, such as DEM, land use/land cover, soils, rainfall, and gullies inventoried through GPS, were combined in a GIS environment. Several terrain and hydrological parameters, like the Stream Power Index and the Topographic Wetness Index, were calculated to express the erosion processes. The 10 gully erosion conditioning factors were evaluated in terms of their weights based on expert opinion and pairwise comparison using the Analytic Hierarchy Process. Weighted Overlay Analysis (WA) in a GIS environment was used to generate a gully erosion susceptibility map with five levels, namely very low, low, moderate, high and very high. High to very high susceptibility areas are dominantly located in steep cultivated lands and hydrologically convergent zones in drainage channels. It has been found that the validation process has confirmed that 80% of the gully sites are classified into moderate and very high susceptibility categories with an R^2 value of 0.75, which shows adequate model performance. The research has proven that the integration of GIS with MCDA (AHP) is a successful methodology in predicting the susceptibility map for gully erosion and provides valuable data on managing and conserving the area of the Ethiopian highlands. Further research may include the use of machine learning.

Keywords: Gully erosion determined: Gully erosion susceptibility: Geospatial analysis: Analytical hierarchy process: Watershed management.

Introduction

Soil is an important natural resource which helps in the functioning of ecosystems and the sustenance of biodiversity and meets the basic needs of humans in terms of food, water, and air. However, even after being so important, soil faces degradation from natural forces along with human interference. Soil erosion is one such type of land degradation problem which is very crucial from an environmental point of view. It restricts agricultural production and the sustainability of the land around the world (Rahmati et al., 2023). Gully erosion is an important type of land degradation problem which creates deep channels with the help of concentrated runoff.

Gully erosion problem is more acute in developing countries, especially in Sub-Saharan Africa, due to the fast-growing population that increases pressure on natural resources and the demand for arable lands, but gully erosion is caused by anthropogenic factors including deforestation, overgrazing, improper use of lands, and improper management of soils. Along with natural factors, such as the presence of steep slopes, high erosivity of soils, and high-intensity rainfalls, anthropogenic pressure leads to faster formation of gullies in watersheds (Arabameri et al., 2020; Mulugeta et al., 2024).

Gully erosion is an environmental and socio-economic issue that negatively affects the livelihoods of rural farmers, the productivity of agriculture and food security, and in the Ethiopian highlands, it persists to hinder sustainable agriculture due to land degradation. Vulnerability of the areas is related to the presence of biophysical and socio-economic characteristics such as rugged terrain, erosive rains, continuous cultivation, low vegetation cover, and poor practice of soil and water conservation techniques (Tadesse and Hailu, 2024; Gelete et al., 2024). Gully erosion is prevalent and acts as a major geo-hydrological process that causes land degradation. Fertile topsoil loss causes depletion of nutrients, loss of soil fertility, and low crop yield (Setargie et al., 2023; Amare et al., 2024). Gully erosion results in various ecological, social, and economic consequences like habitat degradation, fragmentation of ecosystems, sedimentation of water resources, reduction of the level of groundwater, and damage to road infrastructure and human settlements. Therefore, there is a necessity to have an appropriate method of gully erosion assessment, monitoring, and mitigation to control the process and support sustainable land utilization (Yazie et al., 2021 and Gelete et al., 2024).

The knowledge of the distribution and controlling factors of gully erosion will be very important in helping to formulate the right management measures, as gully formation is caused by the interaction of various environmental and human factors, including landform, land use and cover, soil characteristics, rainfall intensity, drainage density and hydrology. Some of the important factors that control gully erosion include slope gradient, stream power index and topographic wetness index (Arabameri et al., 2020). Because gullies don’t form in an even manner within landscapes, there is a need for spatial analysis to find out areas where the risk of gully erosion is high. Advances in geospatial techniques, especially GIS and remote sensing, have played a great role in enhancing the analysis of erosion-prone areas through the integration of data in space.

In addition, incorporation of MCDA, especially the Analytic Hierarchy Process (AHP), offers a very solid and systematic approach to assessment and assignment of weights in terms of the significance of gully erosion conditioning factors. Also, the application of GIS-MCDA (AHP) models greatly improves susceptibility mapping in that they incorporate the nonlinear spatial variation and provide more accurate results compared to empirical or statistical approaches used in soil and water conservation (Mohebzadeh et al., 2024; Mokarram et al., 2024). It is against this background that the objective of this study was to assess the spatial variability and significance of gully erosion influencing factors through GIS-based thematic layers with weights based on MCDA (AHP), and then create a gully erosion susceptibility map using the weighted geospatial layers to prioritize sub-watersheds for conservation planning in the Bale Highlands.

Materials and Methods

Description of the study area

The study area falls within the Bale Zone of Oromia Regional State in southeastern part of Ethiopia, specifically the districts of Agarfa, Dinsho, Goba and Sinana. The Bale Zone is approximately 430 km southeast of Addis Ababa. In terms of geography, the districts of Agarfa, Dinsho, Goba and Sinana fall within latitudes 6°35'0"N to 7°37'0"N and longitudes 39°40'0"E to 40°30'0"E (Figure 1). The area has different land topographies and a bimodal rainfall pattern, which results in different soil erosion hazards. The ruggedness of the terrain and human activities such as farming and deforestation make the area vulnerable to gully erosion.

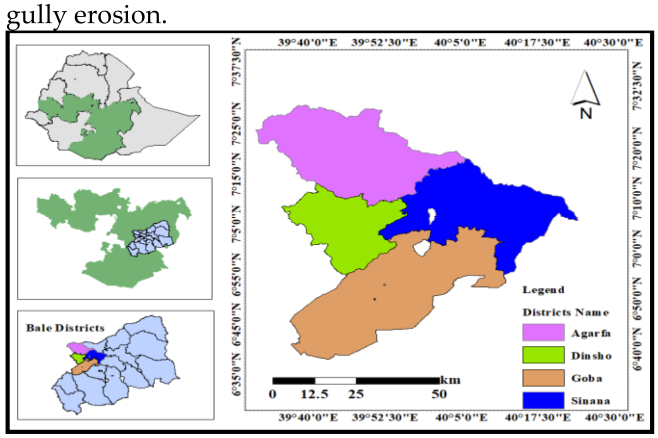

Fig. 1 Map of the selected watershed location in the study district

Sub-watershed Classifications

The categorization of sub-watersheds in the study region (Table 1, Figure 2) shows significant spatial heterogeneity in watershed sizes and their proportionate representation, which carries significant implications for hydrologic response and soil erosion processes. A total of ten sub-watersheds have been identified, showing marked differences in their areal coverage, varying from 4,694.47 ha to 74,513.86 ha. Out of these, WS10 emerges as the largest sub-watershed with a coverage of 74,513.86 ha, representing 27.25% of the entire study area. Following this are WS9 (63,640.17 ha; 23.27%) and WS8 (63,329.83 ha; 23.16%). All three sub-watersheds together account for more than 73% of the total watershed area, suggesting domination of large-sized spatial units (Table 1).

In contrast, the small sub-watersheds, such as WS1 (4,694.47 ha; 1.72%) and WS5 (6,053.06 ha; 2.21%), occupy a negligible share of the total area. Nevertheless, despite their relatively small size, these sub-watersheds may have some specific geomorphologic and land use features, which can cause differences in the intensity of soil erosion and sediment production. The medium-sized sub-watersheds like WS3 (17,709.42 ha; 6.48%) and WS4 (19,577.60 ha; 7.16%) act. The observed variability in sub-watershed size underscores the necessity of adopting a differentiated and scale-sensitive management approach. Larger sub-watersheds may require integrated, basin-wide conservation strategies focusing on upstream–downstream linkages, while smaller sub-watersheds may benefit from targeted, site-specific interventions. Consequently, effective soil and water conservation planning in the study area should be guided by the spatial hierarchy of sub-watersheds to ensure efficient allocation of resources and sustainable watershed management outcomes.

Table 1 Description of the selected sub-watershed classifications

Sub-Watersheds	Area (ha)	Area (%)
WS1	4694.47	1.72
WS2	6371.43	2.33
WS3	17709.42	6.48
WS4	19577.60	7.16
WS5	6053.06	2.21
WS6	10120.94	3.70
WS7	7482.03	2.74
WS8	63329.83	23.16
WS9	63640.17	23.27
WS10	74513.86	27.25

Where, WS = sub-watershed

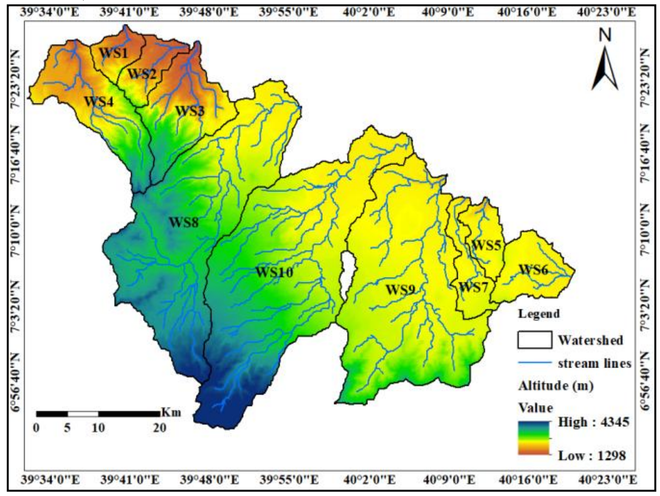

Fig. 2 Sub-watershed map and the drainage lines

Data Sources and Types

Table 2 Detail descriptions of data sources and types

Data Type	Source and Description
Primary Data	GPS-based field survey of existing gullies to validate susceptibility maps.
Topographic Data	Digital Elevation Model (SRTM, ASTER 30 m resolution).
Soil Data	Soil data obtained from laboratory analysis and FAO soil databases.
Land Use/Land Cover	Satellite images (Landsat 8, Sentinel-2).
Rainfall Data	Obtained from meteorological stations.
Slope and Aspect	Derived from DEM analysis.
Stream Density	Extracted from DEM using GIS-based hydrological tools.

Spatial Data Processing

Satellite imagery was corrected for radiometric and geometric distortions and classified using supervised methods to produce the LULC map of the watershed. Soil maps were digitized in ArcGIS and refined using laboratory analysis and FAO soil databases to classify soil types and their erosion susceptibility. A Digital Elevation Model (DEM) with a spatial resolution of 30 m obtained from the Shuttle Radar Topography Mission (SRTM) was used to derive topographic and hydrological parameters relevant to gully erosion susceptibility. Prior to analysis, the DEM was processed in ArcGIS 10.5. Several topographic parameters were derived from the processed DEM, including slope, aspect, flow accumulation, plan curvature and others, which are important terrain attributes influencing hydrological processes and erosion dynamics. These parameters are widely recognized as critical factors influencing runoff generation and gully formation.

Topographic and Hydrological Indices

Several terrain indices were computed from the DEM to quantify the influence of topography and hydrological processes on gully erosion development.

Stream power index (SPI)

The Stream Power Index (SPI) is a commonly used hydrological indicator that represents the erosive power of flowing water. This index takes into consideration both slope gradient and contributing area in determining the amount of potential energy available for transporting sediments and erosion. The Stream Power Index (SPI) was obtained using ArcGIS Spatial Analyst from the DEM in order to determine the erosional potential of surface water and is expressed by the formula:

$$SPI = A \times tan(\beta) \quad \ldots(1)$$

where,
SPI = Stream Power Index
A = Upslope contributing area (flow accumulation)
β = Slope angle (in radians)
tan (β) = Slope gradient (representing terrain steepness)
Higher SPI values indicate areas with greater runoff energy, which are more susceptible to gully initiation and channel erosion.

Plan curvature

The plan form curvature shows the curvature of the land surface at right angles to the direction of the slope and affects the convergence or divergence of the surface runoff. This factor was generated using the Spatial Analyst tool in the ArcGIS environment where negative values (concavity) show flow convergence and higher erosion hazard, positive values (convexity) show flow divergence and lower erosion hazard, while zero values are for flat surfaces.

Topographic wetness index

Topographic Wetness Index (TWI) was used to estimate the spatial distribution of soil moisture and potential water accumulation, which strongly influences runoff concentration and gully formation.

$$TWI = ln\left(\frac{As}{tan(\beta)}\right) \quad \ldots(2)$$

where,
TWI = Topographic Wetness Index
As = Specific catchment area (Flow accumulation × cell size)
β = Local slope angle (in radians)
ln = Natural logarithm
Areas with high TWI values indicate zones of greater water accumulation and soil saturation, increasing the potential for runoff concentration and gully initiation, whereas low TWI values represent well-drained areas with a lower susceptibility to gully erosion.

Multi-Criteria Decision Analysis

Susceptibility to gully erosion was analyzed by employing the Multi-Criteria Decision Analysis (MCDA) method in GIS, where several rasters related to the cause factors were combined. Each of the cause factors has been ranked and assigned weight based on expert opinion, field observation, and literature search. A weighted overlay was performed to generate the map of gully susceptibility.

Analytical hierarchy process

The weights of each criterion were derived using the Analytic Hierarchy Process using a scale of 1-9 following Saaty (1980). The consistency of the weights assigned was validated by computing the Consistency Ratio (CR). The resultant weights were then integrated in a GIS based weighted overlay analysis to produce the gully susceptibility map (Table 4).

Table 4 Saatty's, scale of intensity relative importance

Intensity of relative important	Definition
1	Equal importance
2	Weak or slight
3	Moderate importance
4	Moderate Plus
5	strong importance
6	strong plus
7	Very strong
8	very very strong
9	Extremely importance

The consistency index (CI), which defines the consistency coefficient of the pairwise comparison matrix, was estimated using the given equation.

$$CI = \frac{\lambda max - n}{n-1} \quad \ldots (3)$$

A random consistency index (RI) served as a means of determining the degree of consistency, or a consistency ratio (CR) was calculated using Equ. 4 and Table 5.

$$CR = \left(\frac{CI}{RI}\right) \quad \ldots(4)$$

Table 5 Random consistency index

Matrix size	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

Pairwise Comparison Matrix

Pairwise comparison matrix was developed for those variables which are significant in terms of their influence on the variability of gullies. These variables include Elevation, SPI, Soil Texture, LULC, and Distance to River, TWI, Plan Curvature, Slope Aspect, Slope, and Rainfall. The matrix helped in the ranking of the variables based on their significance.

Table 6 Classification, ranking, and weighting of determinant factors for gully erosion susceptibility mapping

Criteria	Class	Rates	Ranks	Weight
Rainfall (m)	1200 - 1400	Very low	1	25.90
	1400 - 1600	Low	2	
	1600 - 1800	Moderate	3	
	1800 - 2000	High	4	
	>2000	Very high	5	
Distance to River (m)	0 - 50	Very high	5	5.32
	50 - 100	High	4	
	100 - 150	Moderate	3	
	150 - 200	Low	2	
	>200	Very low	1	
LULC	Forest land	Very low	1	17.64
	Shrub land	Low	2	
	Grass land	Moderate	3	
	Settlement	High	4	
	Cultivated land	Very high	5	
Soil Texture	Clay	Very low	1	5.04
	Clay loam	Low	2	
	Sand clay loam, sandy loam, loam	Moderate	3	
	Sandy loam	High	4	
	Silt loam	Very high	5	
SPI	0 – 5.78	Very low	1	3.11
	5.78 – 37.42	Low	2	
	37.42 – 143.88	Moderate	3	
	143.88 – 733.80	High	4	
	>733.80	Very high	5	

Table 7 Classification, ranking, and weighting of determinant factors for gully erosion susceptibility mapping "(…*cont, Table 6*)"

Criteria	Class	Rates	Ranks	Weight
Elevation (m)	<1500	Very low	1	7.99
	1500 - 1900	Low	2	
	1900 - 2700	Moderate	3	
	2700 - 3100	High	4	
	>3100	Very high	5	
Slope (degree)	0 - 5	Very low	1	7.99
	6 - 10	Low	2	
	11 - 15	Moderate	3	
	16 - 20	High	4	
	>25	Very high	5	
Slope aspect	Flat	Negligible	1	3.29
	North	Very Low	2	
	Southwest	Very Low	2	
	North east	Low	3	
	Southeast	Low	3	
	East	Moderate	4	
	Northwest	Moderate	4	
	North	High	5	
Plan curvatur	Convex	Low	1	8.67
	Flat	Moderate	2	

e	Concave	High	3	
TWI	0 – 5	Very low	1	11.18
	5 – 7.5	Low	2	
	7.5 - 11	Moderate	3	
	11 - 14	High	4	
	>14	Very high	5	

Gully Erosion Susceptibility Mapping

Gully erosion susceptibility mapping involved the use of ArcGIS 10.5 software in combination with the Analytical Hierarchy Process (AHP) where several environmental and anthropogenic factors such as elevation, slope, rainfall, and land use were ranked by their importance to gully formation through expert judgments of their pairwise comparisons. The final output is a weighted overlay analysis that incorporates all environmental and anthropogenic factors and produces susceptibility maps of gully formation ranging from very low to very high susceptibility.

Gully inventory map has been developed to map out the existing gullies in the study area. GPS surveys have been performed to get the exact location of gullies while verifying the GPS coordinates using high resolution Google Earth images. The GPS coordinates of the gullies have been compiled in GIS environment to produce an inventory database for gully erosion susceptibility analysis and model validation purposes. Predictive accuracy of the GIS integrated MCDA (AHP) model has been estimated using 30 gully heads locations identified using GPS surveys and mapped in GIS. Each gully point has been assigned with its corresponding susceptibility classes through overlaying on the susceptibility raster. Model performance has been evaluated using the coefficient of determination (R^2) expressed as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad ..(5)$$

where,

y_i = observed values

$\hat{y}_i$ = predicted values

$\bar{y}$ = mean of observed values

Result and Discussion

AHP-Based Pairwise Comparison of Factors Influencing Gully Erosion Susceptibility

From the AHP pair-wise comparison, it emerged that the major factors causing gully erosion susceptibility within the study watershed are elevation, soil texture, stream power index (SPI), rainfall, and land use/land cover (LULC) (Table 8). In line with this, research carried out in Ethiopia demonstrated a high influence of LULC and rainfall on the intensity of gully erosion, underlining the importance of climatic and land cover parameters in susceptibility analysis (Tasew et al., 2026). The use of hydrologic parameters (such as SPI and TWI) along with topographic parameters (slope) has shown a high level of prediction accuracy in gully erosion susceptibility models, which was demonstrated by the field validation of the models in different areas of the world as well as in Ethiopian watersheds (Yang et al., 2025; Mulugeta et al., 2025).

Table 8 Pairwise comparison matrix

Factors	**RF**	**LULC**	**SL**	**EL**	**TX**	**SA**	**SPI**	**CV**	**TWI**	**DRV**
RF	1	2	3	4	5	6	7	3	2	4
LULC	0.5	1	2	3	4	5	5	2	1.5	3
SL	0.33	0.5	1	2	3	4	4	1.5	1	2
EL	0.25	0.33	0.5	1	2	3	3	1	0.75	1.5
TX	0.2	0.25	0.33	0.5	1	2	2	0.5	0.5	1
SA	0.17	0.2	0.25	0.33	0.5	1	1	0.33	0.33	0.75
SPI	0.14	0.2	0.25	0.33	0.5	1	1	0.33	0.25	0.75
CV	0.33	0.5	0.67	1	2	3	3	1	0.75	1.5
TWI	0.5	0.67	1	1.33	2	3	4	1.33	1	2
DRV	0.25	0.33	0.5	0.67	1	1.33	1.33	0.67	0.5	1
Sum	3.67	5.98	9.50	14.16	21.00	29.33	31.33	11.66	8.58	17.50

Where; RF= rainfall, LULC = land use land cover, SL = slope, EL = elevation, TX = texture, SA = slope aspects, SPI = Stream Power Index, CV = Curvature, TWI = Topographic Wetness Index, DRV = distance to river

Relative Contributions of Gully Erosion Susceptibility Determinant Factors

The AHP-GIS model evaluation for the study watershed determined the contribution weight (CW) for the eleven conditioning factors affecting gully erosion susceptibility (Table 9). Therefore, rainfall (25.9 %) was found to be the leading determinant of gully susceptibility, emphasizing its importance in causing runoff and facilitating the erosion processes that lead to gully formation and enlargement in the study watershed. Similarly, current studies have found rainfall and other hydrological parameters to be the major determinants of gully and soil erosion processes in different locations (Phinzi and Szabó, 2024; Liu et al. 2024; Rajabian et al., 2024).

These recent studies have reported rainfall intensity, frequency, or other climatic parameters as the main controls since rainfall directly impacts surface runoff and soil detachment. Conversely, LULC (17.6 %) was the second most significant determinant of gully susceptibility, indicating the role of vegetation cover and land management in determining infiltration capacity, surface roughness, and soil exposure. In agreement with this research, LULC and vegetation indices are important anthropogenic determinants of gully and water erosion susceptibility, particularly in agricultural or bare soils (Phinzi and Szabó, 2024; Liu et al. 2024).

Additionally, topographic characteristics such as slope (11.9 %) and TWI (11.2 %) significantly impacted gully susceptibility by facilitating runoff due to steep slopes and moisture retention due to high TWI areas (Table 9). The results agree with previous studies that revealed land cover and topography to be major factors determining gully erosion risk at global scales (Berihun, 2023). In the chosen watershed, curvature (8.7 %), elevation (8.0 %), and distance to river (5.3 %) had moderate impacts on gully susceptibility due to flow convergence and energy gradient formation (Table 9). In the same way, soil texture (5.0 %), slope aspect (3.3 %), and SPI (3.1 %) had less impact because of precipitation and LULC influences on gully erosion risk in the watershed (Table 9). Similar to the current study, Berihun (2023), Liu et al. (2024), and Rajabian et al. (2024) found out that gully erosion risk is determined by interactions of geomorphological conditions, hydrologic connectivity, and soils.

Table 9 Weighted Contribution of Gully Erosion Factors for Susceptibility Mapping

Factors	RF	LULC	SL	EL	TX	SA	SPI	CV	TWI	DRV	CW	%
RF	0.27	0.33	0.32	0.28	0.24	0.20	0.22	0.26	0.23	0.23	0.26	25.90
LULC	0.14	0.17	0.21	0.21	0.19	0.17	0.16	0.17	0.17	0.17	0.18	17.64
SL	0.09	0.08	0.11	0.14	0.14	0.14	0.13	0.13	0.12	0.11	0.12	11.86
EL	0.07	0.06	0.05	0.07	0.10	0.10	0.10	0.09	0.09	0.09	0.08	7.99
TX	0.05	0.04	0.03	0.04	0.05	0.07	0.06	0.04	0.06	0.06	0.05	5.04
SA	0.05	0.03	0.03	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.03	3.29
SPI	0.04	0.03	0.03	0.02	0.02	0.03	0.03	0.03	0.03	0.04	0.03	3.11
CV	0.09	0.08	0.07	0.07	0.10	0.10	0.10	0.09	0.09	0.09	0.09	8.67
TWI	0.14	0.11	0.11	0.09	0.10	0.10	0.13	0.11	0.12	0.11	0.11	11.18
DRV	0.07	0.06	0.05	0.05	0.05	0.05	0.04	0.06	0.06	0.06	0.05	5.32
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	100.00

Where; RF= rainfall, LULC = land use land cover, SL = slope, EL = elevation, TX = texture, SA = slope aspects, SPI = Stream Power Index, CV = Curvature, TWI = Topographic Wetness Index, DRV = distance to river

Weighted Contributions of Factors Influencing Gully Susceptibility

Assessment of the weight of eleven factors contributing to gully erosion vulnerability was done using the AHP-GIS technique (Table 9). Rainfall (RF, 2.630) emerged as the primary factor followed by land use and land cover (LULC, 1.785), showing the importance of both runoff production and vegetation cover in the control of erosion (Table 10). The topographical factors; slope (SL, 1.191), topographic wetness index (TWI, 1.117), and curvature (CV, 0.864) significantly contributed to gully formation, while the other factors; elevation (EL, 0.792), distance to river (DRV, 0.533), soil texture (TX, 0.497), slope aspect (SA, 0.325), and stream power index (SPI, 0.309) had less influence on gully vulnerability (Table

Table 10 Weighted contributions of factors for gully erosion susceptibility in the watershed

Factors	RF	LULC	SL	EL	TX	SA	SPI	CV	TWI	DRV	WSV
RF	0.260	0.360	0.360	0.320	0.250	0.180	0.210	0.270	0.220	0.200	2.630
LULC	0.130	0.180	0.240	0.240	0.200	0.150	0.150	0.180	0.165	0.150	1.785
SL	0.086	0.090	0.120	0.160	0.150	0.120	0.120	0.135	0.110	0.100	1.191
EL	0.065	0.059	0.060	0.080	0.100	0.090	0.090	0.090	0.083	0.075	0.792
TX	0.052	0.045	0.040	0.040	0.050	0.060	0.060	0.045	0.055	0.050	0.497
SA	0.044	0.036	0.030	0.026	0.025	0.030	0.030	0.030	0.036	0.038	0.325
SPI	0.036	0.036	0.030	0.026	0.025	0.030	0.030	0.030	0.028	0.038	0.309
CV	0.086	0.090	0.080	0.080	0.100	0.090	0.090	0.090	0.083	0.075	0.864
TWI	0.130	0.121	0.120	0.106	0.100	0.090	0.120	0.120	0.110	0.100	1.117
DRV	0.065	0.059	0.060	0.054	0.050	0.040	0.040	0.060	0.055	0.050	0.533
SUM	0.954	1.076	1.140	1.133	1.050	0.880	0.940	1.049	0.944	0.875	10.041

Where; RF= rainfall, LULC = land use land cover, SL = slope, EL = elevation, TX = texture, SA = slope aspects, SPI = Stream Power Index, CV = Curvature, TWI = Topographic Wetness Index, DRV = distance to river

Gully Erosion Susceptibility Determinant Factors

Rainfall, land use land cover, soil texture and stream power index

Erosion susceptibility in the study area depends significantly on the combined effect of rainfall, LULC, soil texture, and SPI, where each of the parameters plays a unique role in the gully erosion process. Areas characterized by high rainfall (>1800 mm) have higher susceptibility because of their high contribution to the generation of runoff and erosive energy. Studies have shown that high rainfall and variability in its rate are one of the strongest climatic factors contributing to the occurrence of gully erosion under varying climatic conditions (Fan et al., 2025 and Liu et al., 2025). Rainfall alone cannot predict the susceptibility of the areas to gully erosion. The contribution of rainfall to the risk of erosion is highly dependent on the land use pattern. The prevalence of cultivated land use makes areas more susceptible to gullies through reducing infiltration and soil cohesion due to vegetation clearance, tilling, and soil exposure. Forested and shrub lands have low erosion susceptibility because of the improved soil stability, interception of rainfall, and enhanced infiltration (Figure 3). This supports the recent discoveries that gully erosion process is considerably enhanced by land-use change and anthropogenic disturbances (Alabi et al., 2025; Kholmurodova et al., 2026). Moreover, soil texture also influences the susceptibility to erosion where clay and silty soils have more vulnerable soils since of their low permeability and weak aggregate stability causing runoff and detachment of particles. These types of soils are well-known as significant factors of erosion susceptibility (Berihun, 2023).

The SPI is the critical factor acting as a topographical and hydrological driver for assessing the erosive force of surface runoff concentration. The current investigation reveals that zones of increased values of SPI which occur mainly at drainage and steep areas are the most vulnerable to gully erosion because of high water concentration and flow velocity (Figure 3). This discovery also confirms the results of previous researches proving the crucial role of topographic control on gully development and expansion (Fan et al., 2025). Zones with high susceptibility are the result of the interaction of heavy rainfall, cultivated land, susceptible soils, and increased SPI, while low susceptibility zones are located only in forest areas with stable soils and low water concentration.

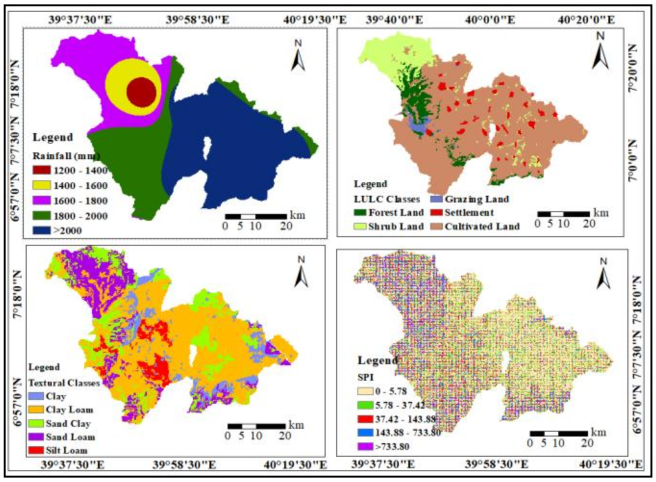

Fig. 3 Selected gully erosion susceptibility determinant factors map

Elevation, plan curvature, topographic wetness index and distance to river

The distribution of the gully erosion determinants (i.e., elevation, plan curvature, TWI, and distance from the river) has shown an evident and well-organized pattern that explains clearly the identified gully susceptibility zones in the map findings (see Figure 4). Based on the map, the low to moderate elevation zones have dominated in the high gully susceptibility zones, whereas the high elevation zones were found in the runoff generation zones that have relatively low gully density. Such finding has proven the fact that the downslope concentration of the runoff energy and sediment is the primary cause of the formation of the gullies.

Similar to this, the curvature map also shows that most gully locations fall within areas that have concave shapes. Convex land forms are predominant within the areas of low susceptibility. This means that surface runoff will be concentrated because of convergence of water flow in the concave shapes hence increasing the shear force and soil detachment processes (Tadele et al., 2024). Convex landforms help in dispersing surface runoff and therefore do not facilitate gully formation. The spatial distribution of the Topographic Wetness Index shows that high TWI values are present in valley bottoms, foot slopes and drainage accumulation areas. The same areas correspond to those areas having high gully susceptibility values and therefore show that soil moisture saturation increases surface runoff incisions (Liu et al., 2024).

In addition, it is quite evident from the distance to rivers map that gullies are mostly formed near rivers within close proximity to river networks, particularly along tributaries and major drainage lines. The above information implies that there is high fluvial hillslope connectivity, whereby the nearness of channels leads to enhanced flow concentration, headcutting retreat, and lateral growth towards uplands (Kebede et al., 2023; Anticho et al., 2026). Generally, the above map outputs indicate that there is high spatial association, whereby the areas with high gully susceptibility are found in low mid-elevation concave topography, with high TWI value and nearness to rivers.

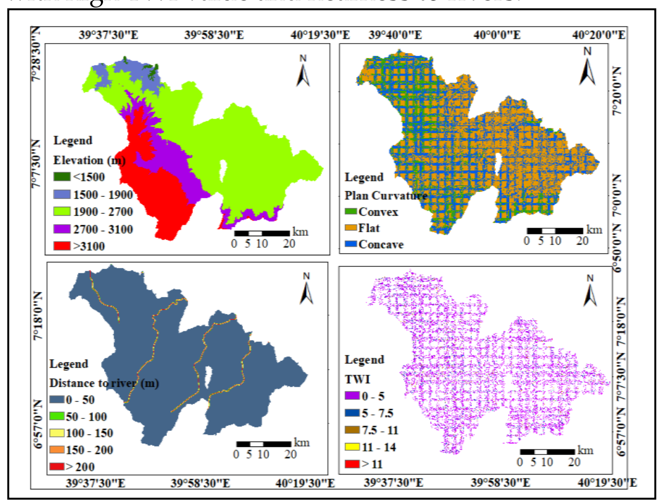

Fig. 4 Selected gully erosion susceptibility determinant factors map

Effect of slope on gully erosion susceptibility determinant factor

As indicated by the analysis of the slope, there exists an evident positive correlation between the slope gradient and gully erosion susceptibility (Figure 5). The high slopes contribute to runoff energy concentration, increase flow velocity, and result in soil detachment. As a consequence, the gullies can easily develop in such an environment. On the contrary, low slopes decrease runoff energy and increase infiltration, thereby making it impossible for erosion to occur in these environments. It is thus evident that the slope is one of the critical topographic factors influencing erosion processes in the study area (Haregeweyn et al., 2023 and Tadesse et al., 2024). Higher slopes increase runoff energy and shearing stress, hence soil detachment and head cut retreat. In other words, the slope acts as one of the fundamental controlling factors in the process of gully erosion susceptibility as it determines the velocity, erosion force, and runoff concentration processes (Zhang et al., 2024).

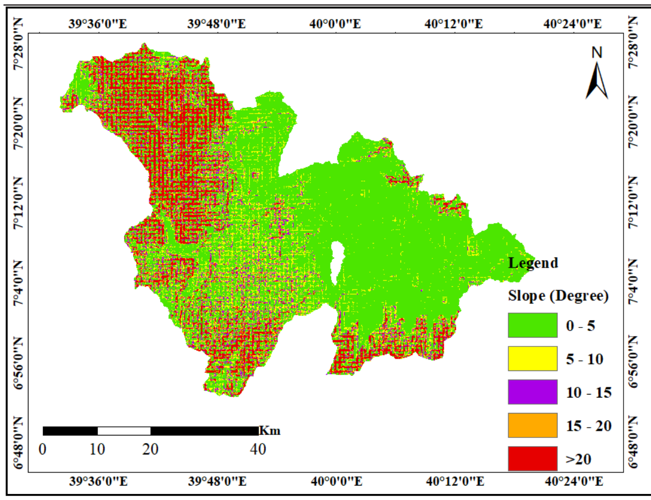

Fig. 5 Slope status as gully erosion susceptibility determinant factor map

Effect of slope aspect on gully erosion susceptibility

The slope aspect per se does not directly cause gully erosion; however, it indirectly causes it by controlling microclimatic and hydrological factors like solar radiation, evaporation, soil moisture content, and vegetation cover (Figure 6). Even though it is less influential than the slope gradient and the intensity of the use of land, the recently developed ensemble models suggest that the inclusion of slope aspect may help in achieving more accurate predictions when used along with the curvature and hydrological indices (Zhang et al., 2024). The impact of this slope factor on gullies is location-specific and acts mainly as a moderator factor affecting the impact of other factors on gully formation. Several studies have found an insignificant correlation between gully incidence and slope aspect due to interactions with other factors like lithology and human disturbances (Li et al., 2024).

Gully Erosion Susceptibility Assessment

Analysis of spatial patterns of gully erosion susceptibility shows significant variability within the watershed, which can be attributed to a complex interplay of topography, hydrology, and land use changes. Susceptibility map (Figure 7) generated by this analysis shows that most of the landscape consists of moderately susceptible areas, whereas highly and very highly susceptible areas are mostly located in structurally and hydrologically sensitive sub-watersheds. The spatial pattern of gully erosion is not governed by one factor; on the contrary, it is caused by the combination of flow accumulation patterns, slope gradient, and human-induced changes to the land surface. Spatial pattern of gully erosion is controlled by flow accumulation, slope gradient, and human-induced changes to the land surface, indicating that gully erosion is a multi-factorial and spatially interactive process, not determined by one particular variable (Tadele et al., 2024 and Zhao et al., 2026).

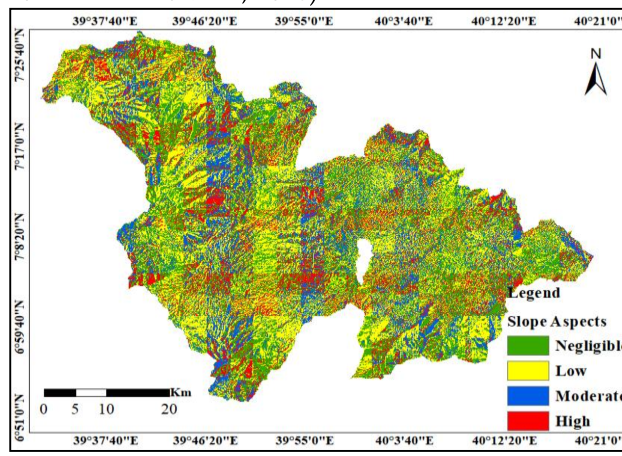

Fig. 6 Slope aspect as gully erosion susceptibility determinant factor map

The central and eastern sub-watersheds have moderate susceptibility because of their slopes and drainage systems in a transitional state, while southern and south-western parts have high to very high susceptibility because of their steep slopes, high flow accumulation, and vegetation cover. Recent studies have confirmed that the ruggedness of the topography and hydrological convergence significantly increase the risk of gully formation (Gelete et al., 2024).

On the other hand, low susceptibility areas will be found on gentle slopes with low drainage density and vegetation cover, which reduce runoff speeds and facilitate infiltration. This finding is consistent with recent findings regarding the protective effect of vegetation and soil stabilization (Peng et al., 2025). Additionally, the tendency for areas of high vulnerability to cluster around the drainage network shows that hydrological connectivity is one of the major forces behind the formation of gullies (Tadele et al., 2024 and Zhao et al., 2026). The formation of gully erosion results from a combination of terrain characteristics, hydrology and land degradation. Recent studies have found slope, flow accumulation, land use change, and distance to streams to be the main factors predicting susceptibility (Gelete et al., 2024). Consequently, this spatial distribution is an indication of the joint effect of natural controls and human activities accelerating land degradation (Figure 7). This highlights the need for integrated structural and biological conservation measures in high-risk areas to reduce runoff connectivity and improve slope stability. Watershed-scale strategies such as reforestation check dams and contour-based structures are widely recommended for effective gully control (Gelete et al., 2024 and Maximus et al., 2025).

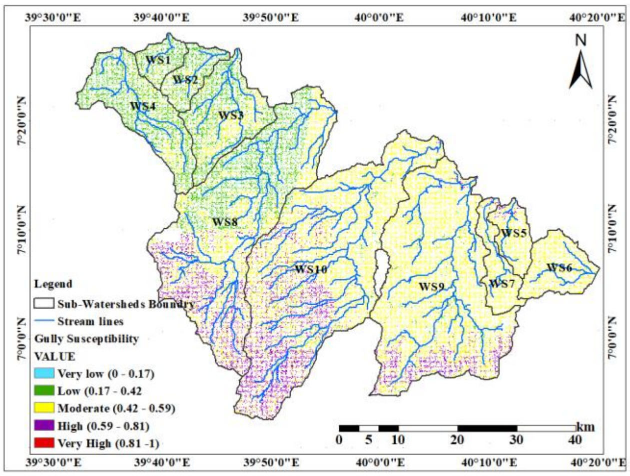

Fig. 7 Gully erosion susceptibility map of the watershed

Validation of Gully Susceptibility Map

Validation of the prediction capacity of the gully susceptibility model was carried out using 30 GPS mapped gully head positions from field surveys. The mapped positions of the gullies were uploaded in ArcGIS (WGS-84) superimposed on the susceptibility map, and then the 'extract Values to Points' function was used to assign a susceptibility class (very low-very high) for each gully. These results demonstrate a high correlation between predicted and observed distribution of gullies, whereby 50% of the gullies are located in high and very high classes while 80% are distributed in moderate to very high classes, reflecting the effectiveness of the weighted overlay model.

The spatial distribution is further justified through the sub-watersheds (WS) analysis, where there are increased numbers of gully distributions in WS8-WS10, which are associated with steep slopes and high drainage density, whereas WS1-WS4 have low numbers of gullies and are mainly associated with low - moderate susceptibility zones; WS5-WS7 are transitional zones. This justifies that most of the gullies exist in erosion prone zones, showing that the susceptibility model is reliable. The model has been able to identify the significant geomorphological factors of gully distribution with an R^2 value of ~0.75, which signifies the model's accuracy (Table 11 and Figure 8).

Table 11 Distribution of gully points across susceptibility classes in the study area

Susceptibility Class	Number of Gully Points	Percentage (%)
Very Low	2	6.7
Low	4	13.3
Moderate	9	30.0
High	10	33.3
Very High	5	16.7
Total	30	100

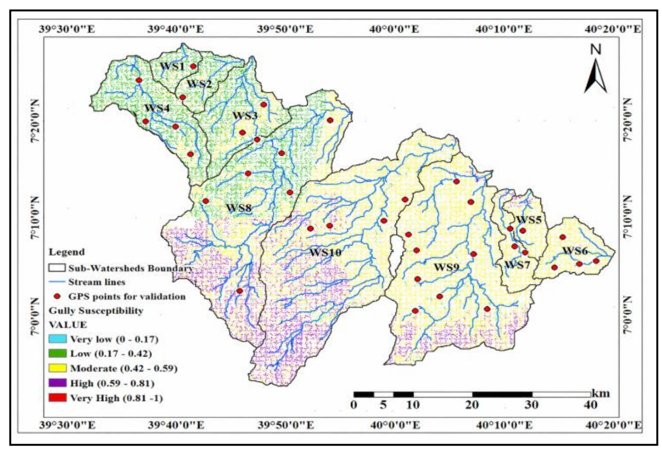

Fig. 8 Validated gully erosion susceptibility map of the watershed

Conclusions

To conclude, the combination of geospatial analysis methods and Multi-Criteria Decision Analysis using the Analytic Hierarchy Process was found to be a highly useful and reliable method to analyze and map the susceptibility of gully erosion in the Bale Highlands area. The research has shown that gully erosion is affected by several environmental and anthropogenic factors; however, the main factors determining the extent of erosion are rainfall and land use/land cover. Furthermore, the most significant variables that affect gully erosion in the study area, after rainfall and land use/land cover, are slope and topographic wetness index. According to the results of the spatial analysis conducted, the zones of moderate and high susceptibility to gully erosion are found to be located mainly in areas with steep slopes, high rainfall, cultivations, and hydrologic connectivity. The good agreement between the susceptibility predicted and observed gullies indicates the efficiency of the applied method and its reliability. Overall, the findings significantly contribute to advancing sustainable land management practices and reducing land degradation in erosion-vulnerable highland regions.

Based on the findings of this study, it is strongly recommended that priority attention be given to high and very high susceptibility zones for immediate and targeted intervention to effectively reduce ongoing gully expansion and land degradation. It is also recommended to promote sustainable land use practices by minimizing cultivation on steep slopes and enhancing vegetation cover through agroforestry and controlled grazing, while strengthening watershed based management approaches to address erosion processes holistically. Further studies should incorporate advanced machine learning models and higher-resolution datasets to improve prediction accuracy, while also emphasizing long-term monitoring of gully dynamics and evaluation of conservation effectiveness.

Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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