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Research Article

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

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Abstract

Soil erosion, particularly gully erosion, is a major form of land degradation threatening agricultural productivity, ecosystem stability, and rural livelihoods in the Ethiopian highlands. The aim of this study was to assess the spatial variability and relative influence of gully erosion conditioning factors and to develop a gully erosion susceptibility map for prioritizing sub-watersheds for soil and water conservation interventions in the Bale Highlands. Multi-source spatial datasets, including Digital Elevation Models, land use/land cover, soil properties, rainfall, and GPS-based gully inventory data, were integrated within a GIS framework. Key terrain and hydrological indices, including the Stream Power Index and Topographic Wetness Index, were derived to represent erosion-related processes. Ten gully erosion conditioning factors were identified and weighted using the Analytic Hierarchy Process based on expert judgment and pairwise comparison. A GIS-based weighted overlay analysis was applied to produce a susceptibility map classified into five classes: very low, low, moderate, high, and very high. Results show that rainfall (25.9%) and land use/land cover (17.6%) are the most influential factors, followed by slope (11.9%) and TWI (11.2%). High and very high susceptibility zones are mainly concentrated in steep cultivated areas and hydrologically convergent zones along drainage networks. Model validation indicates that 80% of observed gully locations fall within moderate to very high susceptibility classes, with an R^2 of 0.75, demonstrating good predictive performance. The study confirms that GIS and MCDA (AHP) integration is an effective approach for gully erosion susceptibility mapping and provides useful information for targeted land management and conservation planning in the Ethiopian highlands. Further studies should incorporate advanced techniques such as machine learning to improve the accuracy of gully erosion prediction and enhance monitoring of gully dynamics.

Keywords: *Gully erosion determined, Gully Erosion Susceptibility, Geospatial Analysis, Analytical Hierarchy Process, Watershed Management.*

Introduction

Soil is a vital natural resource that underpins ecosystem functioning, sustains biodiversity, and fulfills essential human needs through the provision of food, clean water, and air. Despite its fundamental importance, soil is increasingly degraded due to the combined influence of natural processes and human activities. Among the various forms of land degradation, soil erosion remains one of the most critical environmental challenges, significantly constraining agricultural productivity, ecosystem stability, and sustainable land management worldwide (Rahmati *et al*., 2023). Gully erosion is a severe form of land degradation that forms deep channels under concentrated runoff, leading to rapid soil loss, reduced land productivity, increased sedimentation, and long-term threats to sustainable agriculture and watershed management.

The severity of gully erosion is particularly pronounced in developing regions, especially in Sub-Saharan Africa, where rapid population growth and increasing demand for agricultural land intensify pressure on natural resources, while gully formation is strongly driven by anthropogenic factors such as deforestation, overgrazing, inappropriate land-use practices, and poor soil management. In combination with natural conditions such as steep slopes, highly erodible soils, and intense rainfall events, human-induced pressures significantly accelerate the initiation and expansion of gullies within watersheds (Arabameri *et al*., 2020; Mulugeta *et al*., 2024).

Gully erosion is a major environmental and socio-economic problem, reducing rural livelihoods, agricultural productivity, and food security, and in Ethiopia's highlands it continues to limit sustainable agricultural production through ongoing land degradation. The vulnerability of these areas is linked to a combination of biophysical and socio-economic factors, including rugged topography, erosive rainfall patterns, continuous cultivation, limited vegetation cover, and inadequate soil and water conservation practices (Tadesse and Hailu, 2024; Gelete *et al*., 2024). Gully erosion is widespread and represents a dominant geo-hydrological process driving land degradation. The removal of fertile topsoil leads to significant nutrient depletion, declining soil fertility, and reduced crop yields (Setargie *et al*., 2023 and Amare *et al*., 2024).

Gully erosion leads to widespread ecological, social, and economic impacts, including habitat destruction, ecosystem fragmentation, sedimentation of water bodies, groundwater decline, and damage to infrastructure such as roads and settlements. These cumulative impacts undermine rural livelihoods and local development, highlighting the urgent need for effective assessment, monitoring, and management strategies to control gully erosion and promote sustainable land use (Yazie *et al*., 2021 and Gelete *et al*., 2024).

Understanding the spatial distribution and controlling factors of gully erosion is essential for designing targeted and cost-effective land management interventions, as gully formation results from the interaction of environmental and human factors such as topography, land use and cover, soil properties, rainfall intensity, drainage density, and hydrological conditions. Key variables such as slope gradient, stream power index, and topographic wetness index have been identified as critical determinants of gully erosion susceptibility (Arabameri *et al*., 2020). Since gullies do not develop uniformly across landscapes, spatially explicit analysis is required to identify high-risk areas and prioritize intervention efforts. Recent advances in geospatial technologies, particularly GIS and remote sensing, have significantly improved the high-accuracy mapping and analysis of erosion-prone areas by enabling the integration of diverse spatial datasets and the effective assessment of complex interactions among factors driving gully erosion.

Furthermore, integrating multi-criteria decision analysis (MCDA), particularly the Analytic Hierarchy Process (AHP), provides a robust and structured framework for evaluating and weighting the relative importance of gully erosion conditioning factors. In addition, GIS-based MCDA (AHP) models significantly enhance susceptibility mapping by capturing nonlinear spatial variability and delivering more reliable results than traditional empirical or statistical methods for prioritizing soil and water conservation interventions (Mohebzadeh *et al*., 2024; Mokarram *et al*., 2024). Therefore, the aim of this study was to quantify the spatial variability and relative influence of gully erosion determinant factors using GIS-based thematic layers weighted through Multi-Criteria Decision Analysis (MCDA) with the Analytical Hierarchy Process (AHP), and to develop a gully erosion susceptibility map by integrating these weighted geospatial layers to prioritize sub-watersheds for targeted soil and water conservation planning and interventions in the Bale Highlands.

Materials and Methods

Description of the study area

The study area is located in the Bale Zone of Oromia Regional State, southeastern Ethiopia, covering Agarfa, Dinsho, Goba, and Sinana districts (Figure 1). Bale Zone is situated about 430 kilometers southeast of Addis Ababa. Geographically, the districts of Agarfa, Dinsho, Goba, and Sinana lie between latitudes 6°35'0" N to 7°37'0" N, and longitudes 39°40'0" E to 40°30'0" E (Figure 1). This region features diverse topography and a bimodal rainfall pattern, contributing to variable soil erosion risks. Steep and uneven terrain, along with human activities like farming and deforestation, heightens the risk of gully erosion.

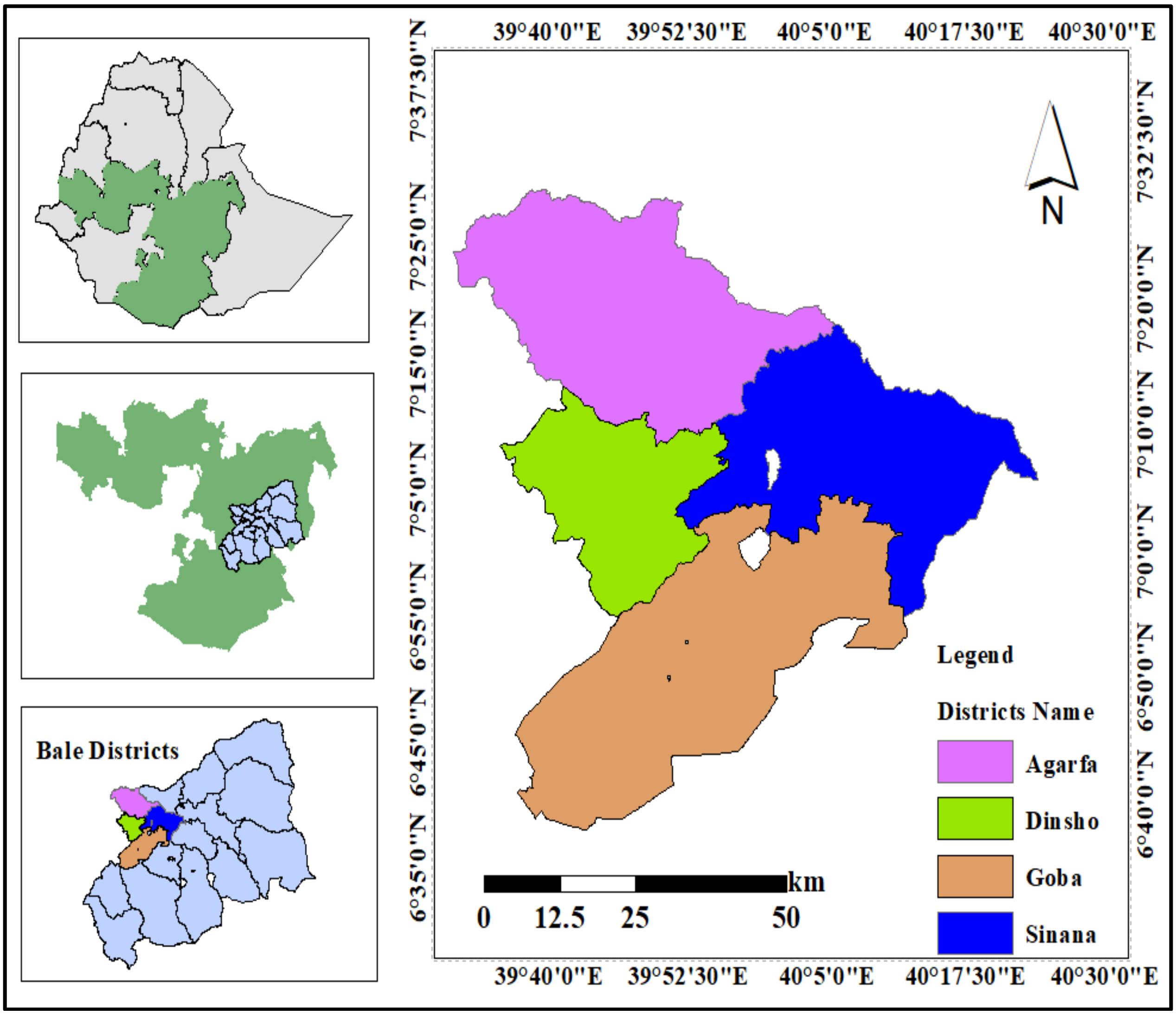

Figure 1. Map of the selected watershed location in the study district.

Methodology

Sub watershed Classifications

The classification of sub-watersheds within the study area (Table 1; Figure 2) reveals pronounced spatial heterogeneity in watershed size and proportional coverage, which has important implications for hydrological behavior and soil erosion dynamics. A total of ten sub-watersheds were delineated, exhibiting considerable variation in areal extent, ranging from 4,694.47 ha to 74,513.86 ha. Among these, WS10 constitutes the largest sub-watershed, covering 74,513.86 ha and accounting for 27.25% of the total study area. This is followed by WS9 (63,640.17 ha; 23.27%) and WS8 (63,329.83 ha; 23.16%). Collectively, these three sub-watersheds represent more than 73% of the total watershed area, indicating a strong dominance of large spatial units in the landscape structure (Table 1). Such extensive sub-watersheds are likely to exert a substantial influence on runoff generation, sediment transport, and overall watershed hydrology.

In contrast, smaller sub-watersheds, including WS1 (4,694.47 ha; 1.72%) and WS5 (6,053.06 ha; 2.21%), contribute only a marginal proportion of the total area. Despite their limited spatial extent, these smaller units may exhibit distinct geomorphological and land-use characteristics, potentially leading to localized variations in erosion intensity and sediment yield. Medium-sized sub-watersheds such as WS3 (17,709.42 ha; 6.48%) and WS4 (19,577.60 ha; 7.16%) represent transitional units that may integrate both localized and broader-scale hydrological processes (Table 1). 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

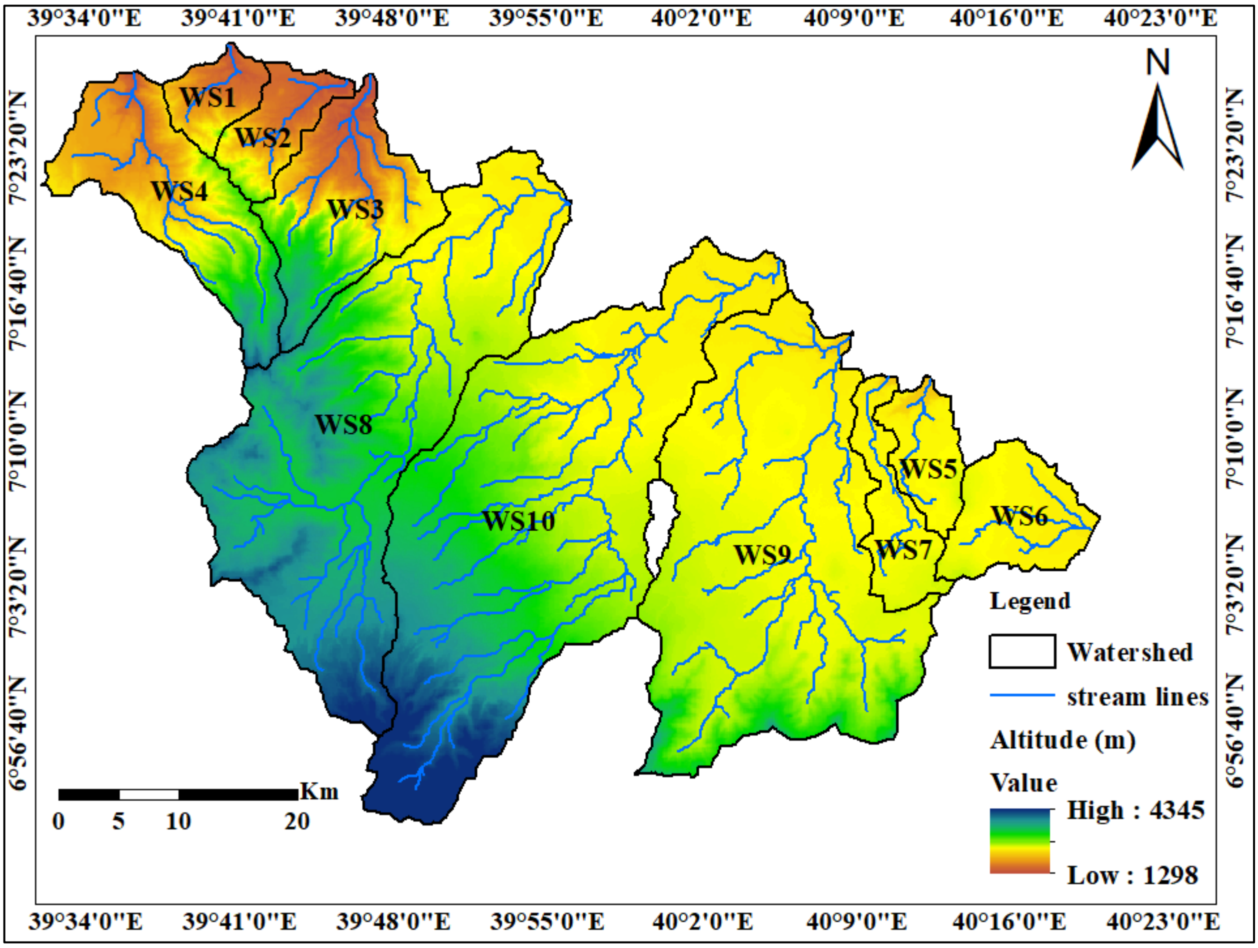

Figure 2. Sub-watershed map and the drainage lines

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.

Software and Tools Used

Table 3. Software and Tools its purpose of used

Software and Tools	Purposed of used
GIS	ArcGIS 10.5 for spatial data processing and overlay analysis
Remote Sensing	ERDAS Imagine for satellite image classification
AHP	Excel-based AHP template for consistency ratio analysis
Statistical Analysis	validation and accuracy assessment
Google Earth Pro	visual interpretation and field validation

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**.** It combines the effects of slope gradient and contributing area to estimate the potential energy available for sediment transport and channel incision. Using ArcGIS Spatial Analyst**,** the Stream Power Index (SPI) was derived from the DEM to estimate the erosive power of surface runoff and was calculated using the following equation:

$$\boldsymbol{SPI = A \times tan(\beta)} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \quad \mathbf{(1)}$$

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

Plan curvature represents the curvature of the land surface perpendicular to the slope direction and controls the convergence or divergence of surface runoff. It was derived using the ArcGIS Spatial Analyst tool, where negative values (concave) indicate flow convergence and higher gully erosion risk, positive values (convex) indicate flow divergence and lower erosion susceptibility, and zero values represent flat areas with minimal influence on runoff distribution.

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.

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

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

Gully erosion susceptibility was assessed using Multi-Criteria Decision Analysis (MCDA) in GIS, integrating multiple raster layers of causative factors. Each factor was ranked and weighted based on expert judgment, field observations, and literature review. A weighted overlay analysis combined the factors to produce a spatially explicit map of gully susceptibility, highlighting areas at varying risk levels.

Analytical Hierarchy Process

Weights for each factor were calculated using the Analytical Hierarchy Process (AHP) with a 1–9 scale based on Saaty (1980). Consistency of the assigned weights was verified using the Consistency Ratio (CR). The weighted factors were then combined in a GIS-based weighted overlay to generate the final 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 (Equation 7).

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

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

$$\mathbf{CR} = \left(\frac{\mathbf{CI}}{\mathbf{RI}}\right) \qquad (4)$$

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

A pairwise comparison matrix was constructed for key factors influencing gully variability, including Elevation, SPI, Soil Texture, LULC, and Distance to River, TWI, Plan Curvature, Slope Aspect, Slope, and Rainfall. The matrix facilitated a structured ranking of factors, reflecting their relative impact on gully erosion (Table 6 and Table 7).

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 curvature	Convex	Low	1	8.67
	Flat	Moderate	2	
	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 was robustly mapped using ArcGIS 10.5 integrated with the Analytical Hierarchy Process (AHP), where key environmental and anthropogenic factors elevation, slope, rainfall, and land use were systematically weighted through expert-driven pairwise comparisons. A weighted overlay analysis synthesized these factors into a spatially explicit susceptibility map, categorizing the landscape from very low to very high risk. The map's precision was rigorously validated against GPS surveyed gullies, ensuring reliable delineation of vulnerable zones.

Gully Erosion Susceptibility Map Validation

A gully inventory map was prepared to identify and document existing gullies within the watershed. Field surveys using GPS were conducted to collect precise coordinates of active gullies, and the data were further verified using high-resolution Google Earth imagery. The validated gully points were integrated into a GIS environment to produce a reliable inventory dataset used for gully erosion susceptibility analysis and model validation. The predictive accuracy of the GIS-based integrated MCDA (AHP) model was assessed using 30 GPS-mapped gully head locations, which were overlaid on the susceptibility raster to assign each gully a corresponding susceptibility class. Model performance was quantified using the coefficient of determination (R^2) calculated as:

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

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

The AHP pairwise comparison (Table 8) identified elevation, soil texture, and stream power index (SPI), rainfall, and land use/land cover (LULC) as the most influential factors driving gully erosion susceptibility in the study watershed. Consistent with this, studies in Ethiopia reported strong effects of LULC and rainfall on gully severity, emphasizing the role of climatic and land cover dynamics in susceptibility mapping (Tasew *et al.,* 2026). Integration of topographic and hydrological variables such as slope, SPI, and TWI has shown high predictive performance in gully susceptibility modeling, with field-validated studies globally and in Ethiopian watersheds highlighting elevation and TWI as key controls on runoff concentration and soil detachment (Yang *et al.*, 2025; Mulugeta *et al.*, 2025). These findings collectively support the robustness of the AHP-GIS gully susceptibility map for targeted soil and water conservation planning.

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 analysis of the study watershed quantified the weighted contribution (CW) of eleven conditioning factors influencing gully erosion susceptibility (Table 9). Accordingly, rainfall (25.9 %) was the dominant driver of gully susceptibility, underscoring its pivotal role in generating runoff and driving the erosive processes that initiate and expand gullies in the study watershed. Consistently, recent studies report rainfall and related hydrological metrics as primary factors controlling gully and soil erosion processes across diverse environments (Phinzi and Szabó, 2024; Liu *et al*. 2024; Rajabian *et al*., 2024). These studies often report rainfall intensity, frequency, or related climatic indices as primary controls due to their direct effect on surface runoff and soil detachment.

On the other hand, LULC (17.6 %) was the second most influential factor controlling gully susceptibility, highlighting the role of vegetation cover and land management in regulating infiltration, surface roughness, and soil exposure. In line with this study, LULC and vegetation indices are key anthropogenic controls on gully and water erosion susceptibility, especially where agricultural or bare soils promote overland flow (Phinzi and Szabó, 2024; Liu *et al*., 2024).

Topographic factors such as slope (11.9 %) and TWI (11.2 %) also contributed substantially, with steeper slopes accelerating runoff and high TWI areas promoting moisture accumulation and surface saturation (Table 9). These findings align with global evidence that land cover and topography are critical determinants of erosion risk across diverse landscapes (Berihun, 2023). In the selected watershed, curvature (8.7 %), elevation (8.0 %), and distance to river (5.3 %) exerted moderate influence on gully susceptibility, reflecting their role in directing flow convergence and shaping local energy gradients. Similarly, soil texture (5.0 %), slope aspect (3.3 %), and SPI (3.1 %) had lower contributions, related to rainfall and LULC factors on gully susceptibility in the watershed (Table 9). In line with the current study, Berihun (2023), Liu *et al* (2024), and Rajabian *et al* (2024) reported that terrain morphology, hydrological connectivity, and soil properties interact to influence gully erosion susceptibility.

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

The weighted contributions of eleven conditioning factors on gully susceptibility were assessed using the AHP-GIS framework (Table 9). Rainfall (RF, 2.630) was the dominant driver, followed by land use and land cover (LULC, 1.785), highlighting the critical roles of runoff generation and vegetation in controlling erosion (Table 10). Topographic factors slope (SL, 1.191), topographic wetness index (TWI, 1.117), and curvature (CV, 0.864) also significantly influenced gully formation, while 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 lesser effects, indicating that climatic and major landscape features primarily govern gully susceptibility (Table 10).

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

Gully erosion susceptibility in the study area is strongly controlled by the interaction of rainfall, land use/land cover (LULC), soil texture, and the Stream Power Index (SPI), with each factor playing a distinct but interrelated role in driving erosion processes. High rainfall zones (>1800 mm) exhibit significantly greater susceptibility due to increased runoff generation and erosive energy, which accelerates soil detachment and gully incision (Figure 3). Recent studies confirm that rainfall intensity and variability are among the most influential climatic drivers of gully erosion, particularly under changing climate conditions (Fan *et al*., 2025 and Liu *et al*., 2025).

However, rainfall alone does not determine erosion risk; its impact is strongly mediated by land use. The dominance of cultivated land in the watershed increases susceptibility due to vegetation removal, frequent tillage, and soil exposure, all of which reduce infiltration and soil cohesion. In contrast, forest and shrub lands demonstrate lower susceptibility by enhancing soil stability, intercepting rainfall, and promoting infiltration. This agrees with recent findings that land-use change and anthropogenic disturbance significantly amplify gully erosion processes (Alabi *et al*., 2025; Kholmurodova *et al*., 2026). Soil texture further conditions susceptibility, with clay and silt-dominated soils showing higher vulnerability due to low permeability and weak aggregate stability, which promote surface runoff and particle detachment (Figure 3). These soil characteristics are widely recognized as key determinants of erosion sensitivity (Berihun, 2023).

The Stream Power Index (SPI) plays a decisive role as a hydrological and topographic driver by quantifying the erosive power of concentrated surface runoff. In this study, areas with high SPI values typically along drainage channels and steep slopes exhibit the greatest susceptibility to gully erosion due to increased flow accumulation and velocity (Figure 3). This finding is consistent with previous studies, confirming the fundamental influence of topographic controls on gully initiation and expansion (Fan et al., 2025). Overall, high susceptibility zones are associated with the combined effects of intense rainfall, cultivated land, erodible soils, and elevated SPI, whereas low susceptibility areas are mainly confined to forested regions characterized by stable soils and limited flow concentration.

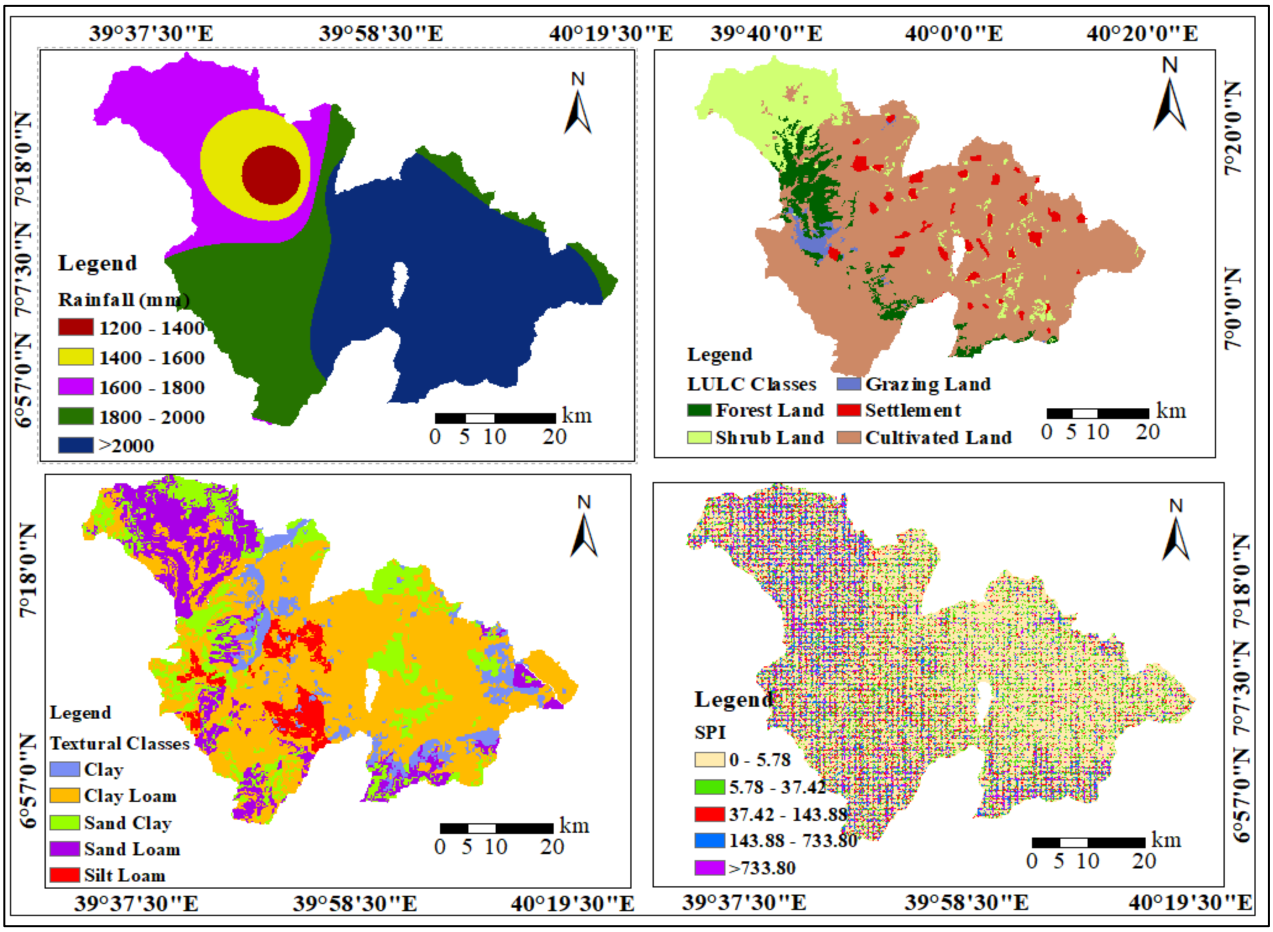

Figure 3. Selected gully erosion susceptibility determinant factors map.

Elevation, Plan Curvature, Topographic Wetness Index and Distance to River

The spatial distribution of gully erosion determinant factors (elevation, plan curvature, Topographic Wetness Index (TWI), and distance to river) shows a consistent and strongly structured pattern that clearly explains the susceptibility zones identified in the map results (Figure 4). The map indicates that low to mid-elevation zones dominate high susceptibility areas, while higher elevations mainly correspond to runoff generation zones with relatively lower gully concentration. This pattern confirms that downslope accumulation of runoff energy and sediment is the main driver of gully formation, where converging flow paths intensify erosional processes in intermediate terrain positions (Setargie *et al*., 2023 and Gelete *et al*., 2024).

Similarly, the plan curvature map shows that concave landforms spatially overlap with most gully-prone areas, while convex areas dominate low susceptibility zones. This indicates that flow convergence in concave terrain concentrates surface runoff, increases shear stress, and accelerates soil detachment, directly supporting observed gully clusters in the mapped concave valleys and depressions (Tadele *et al*., 2024). In contrast, convex slopes act as dispersal zones, reducing runoff concentration and limiting gully initiation. The TWI spatial pattern strongly aligns with mapped gully hotspots, where high TWI values are concentrated in valley bottoms, foot slopes, and drainage accumulation zones. These same areas correspond to the highest predicted susceptibility in the map, confirming that soil moisture saturation reduces soil shear strength and promotes surface incision during rainfall events. This hydrological accumulation effect is a key trigger for gully initiation in the mapped low-lying wet areas (Liu *et al*., 2024).

Furthermore, the distance-to-river map clearly shows that most gullies are located within close proximity to river networks, especially along tributaries and main drainage lines. This spatial coincidence indicates strong fluvial hillslope connectivity, where channel proximity enhances flow concentration, promotes headcut retreat, and accelerates lateral gully expansion toward uplands (Kebede *et al*., 2023 and Anticho *et al*., 2026). Overall, the integrated map results demonstrate a clear spatial agreement: high gully susceptibility zones are concentrated in low mid elevation concave terrain, with high TWI values and close proximity to river channels, confirming that topography and hydrological connectivity jointly control gully erosion development in the study area (Figure 4).

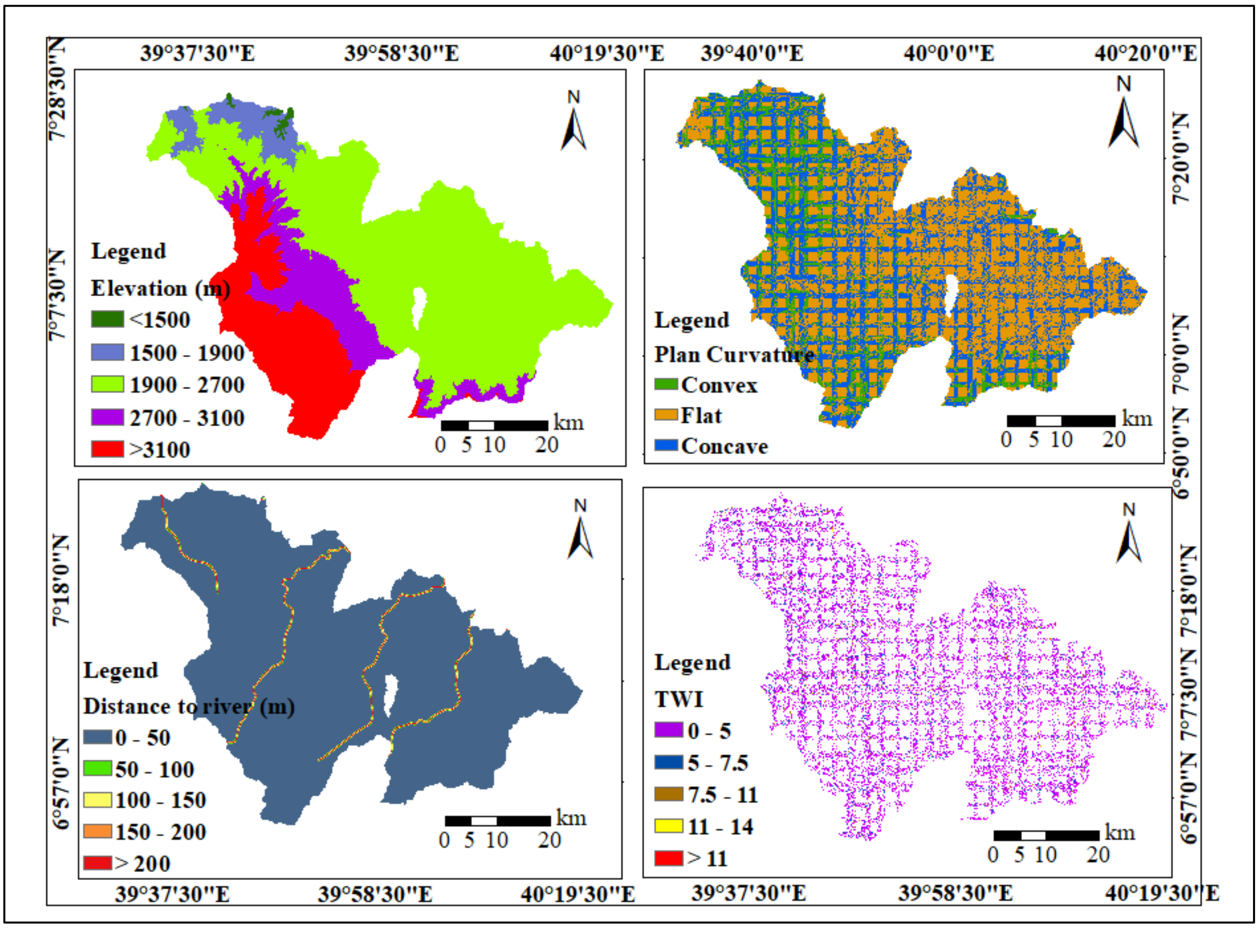

Figure 4. Selected gully erosion susceptibility determinant factors map

Effect slope on Gully Erosion Susceptibility

Slope based analysis shows a clear positive relationship between slope gradient and gully erosion susceptibility (Figure 5). Steep and moderately steep slopes concentrate runoff energy, increase flow velocity, and enhance soil detachment, making them highly prone to gully formation. In contrast, gentle slopes reduce runoff intensity and promote infiltration, resulting in lower erosion risk. This pattern confirms that slope is a key terrain factor controlling erosion processes in the study area (Haregeweyn *et al*., 2023 and Tadesse *et al*., 2024). Steeper slopes increase surface runoff energy and shear stress, accelerating soil detachment and head-cut retreat. Slope plays a fundamental controlling role in gully erosion susceptibility because it regulates runoff velocity, erosion force, and flow concentration, which determine gully initiation and expansion processes (Zhang *et al.,* 2024). In contrast, areas with gentle slopes are generally more stable due to lower flow energy and weaker erosive forces.

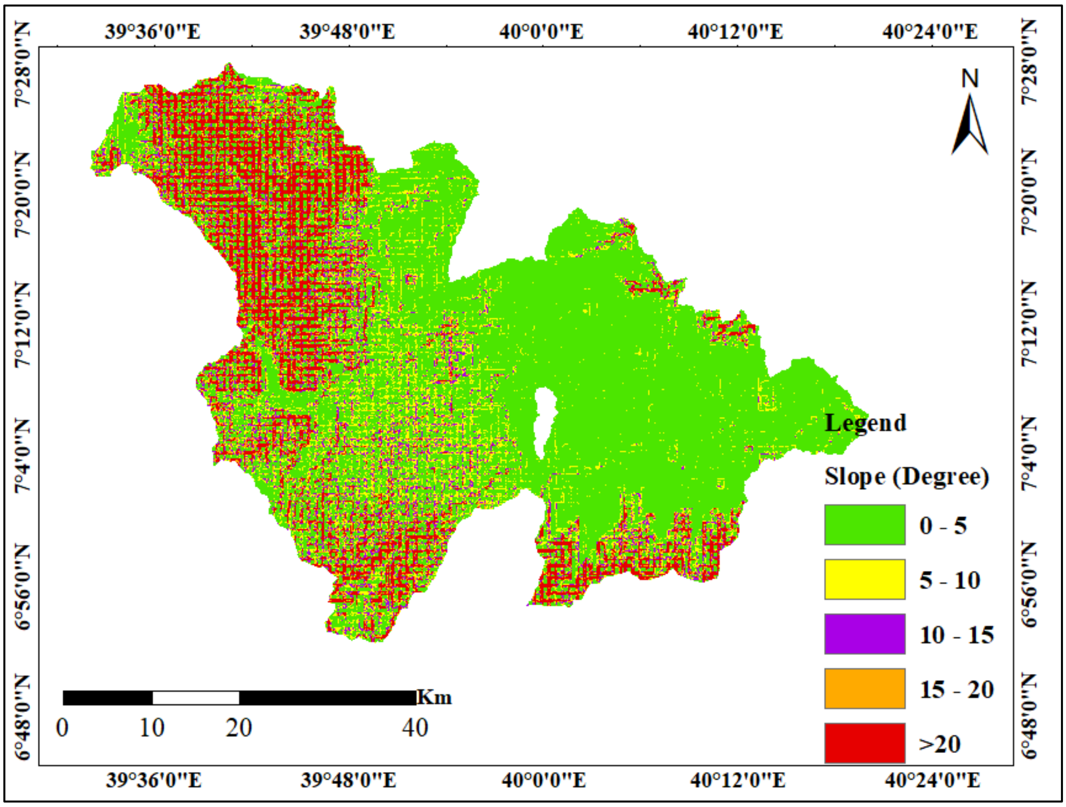

Figure 5. Slope status as gully erosion susceptibility determinant factor map

Effect slope aspect on Gully Erosion Susceptibility

Slope aspect does not directly drive gully erosion but indirectly influences it by regulating microclimatic and hydrological conditions such as solar radiation, evapotranspiration, soil moisture, and vegetation cover (Figure 6). Although generally weaker than slope gradient and land use intensity, recent ensemble models show that including aspect can improve prediction accuracy when combined with curvature and hydrological indices (Zhang *et al*., 2024). Its effect is spatially variable and largely functions as a moderating factor shaping the influence of other topographic and anthropogenic drivers on gully development. Accordingly, several studies report weak or inconsistent relationships with gully occurrence due to strong interactions with lithology and human disturbance (Li *et al*., 2024), confirming its role as a secondary rather than primary control.

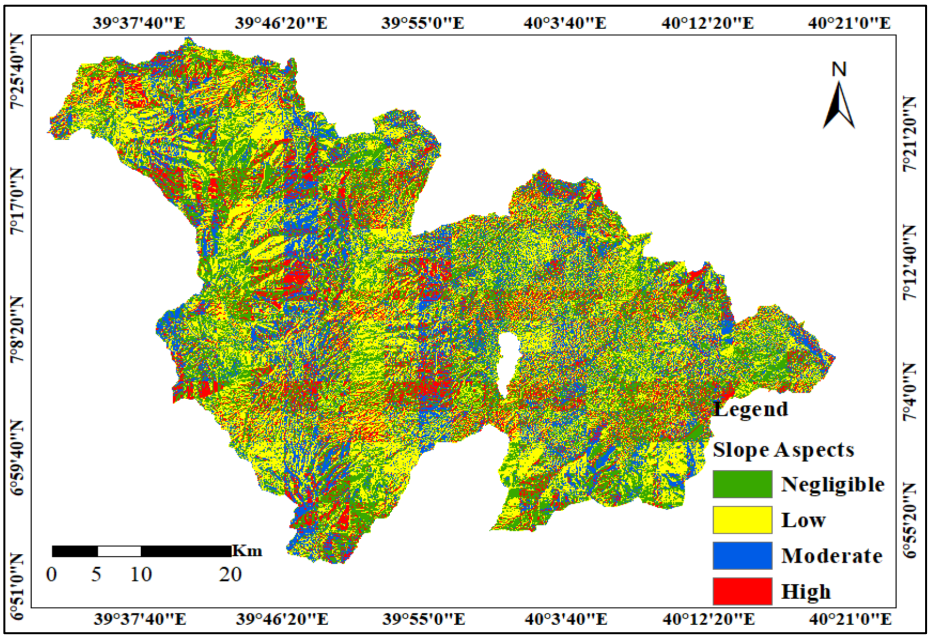

Figure 6. Slope aspect as gully erosion susceptibility determinant factor map

Gully Erosion Susceptibility Assessment

The spatial analysis of gully erosion susceptibility reveals a pronounced heterogeneity across the watershed, reflecting the complex interaction between topography, hydrological processes, and land use dynamics. The resulting susceptibility map (Figure 7) demonstrates that moderate susceptibility classes dominate the landscape, while high and very high susceptibility zones are concentrated in structurally and hydrologically sensitive sub-watersheds. The spatial distribution of gully erosion is not controlled by a single factor but results from the combined influence of flow accumulation pathways, slope gradient, and human-induced land surface disturbances. The spatial distribution of gully erosion is jointly controlled by flow accumulation, slope gradient, and human-induced land surface disturbances, confirming that erosion are a multi-factorial and spatially interconnected process rather than driven by a single variable (Tadele *et al.*, 2024 and Zhao *et al.*, 2026).

The central and eastern sub-watersheds show moderate susceptibility due to transitional slopes and developing drainage networks, while the southern and south-western areas exhibit high to very high susceptibility driven by steep slopes, high flow accumulation, and sparse vegetation. Recent studies confirm that terrain ruggedness and hydrological convergence strongly increase gully initiation risk (Gelete *et al.*, 2024), as these conditions enhance runoff energy beyond soil resistance, promoting headcut development and gully expansion.

Conversely, low susceptibility zones occur on gentle slopes with low drainage density and stable vegetation, reducing runoff velocity and enhancing infiltration. This supports recent findings on the protective role of vegetation and soil stability (Peng *et al.*, 2025). Moreover, the clustering of high-risk areas along drainage networks highlights hydrological connectivity as a key driver of gully development (Tadele *et al.*, 2024 and Zhao *et al.*, 2026). Gully erosion is a multi-factorial process driven by terrain, hydrology, and land degradation. Recent studies identify slope, flow accumulation, land use change, and distance to streams as key predictors of susceptibility (Gelete *et al.*, 2024). Thus, the observed spatial pattern reflects the combined effects of natural controls and human-induced disturbances accelerating land degradation and more increase gully susceptibility (Figure 7).

The dominance of moderate to high susceptibility indicates a high risk of continued gully expansion without intervention. 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).

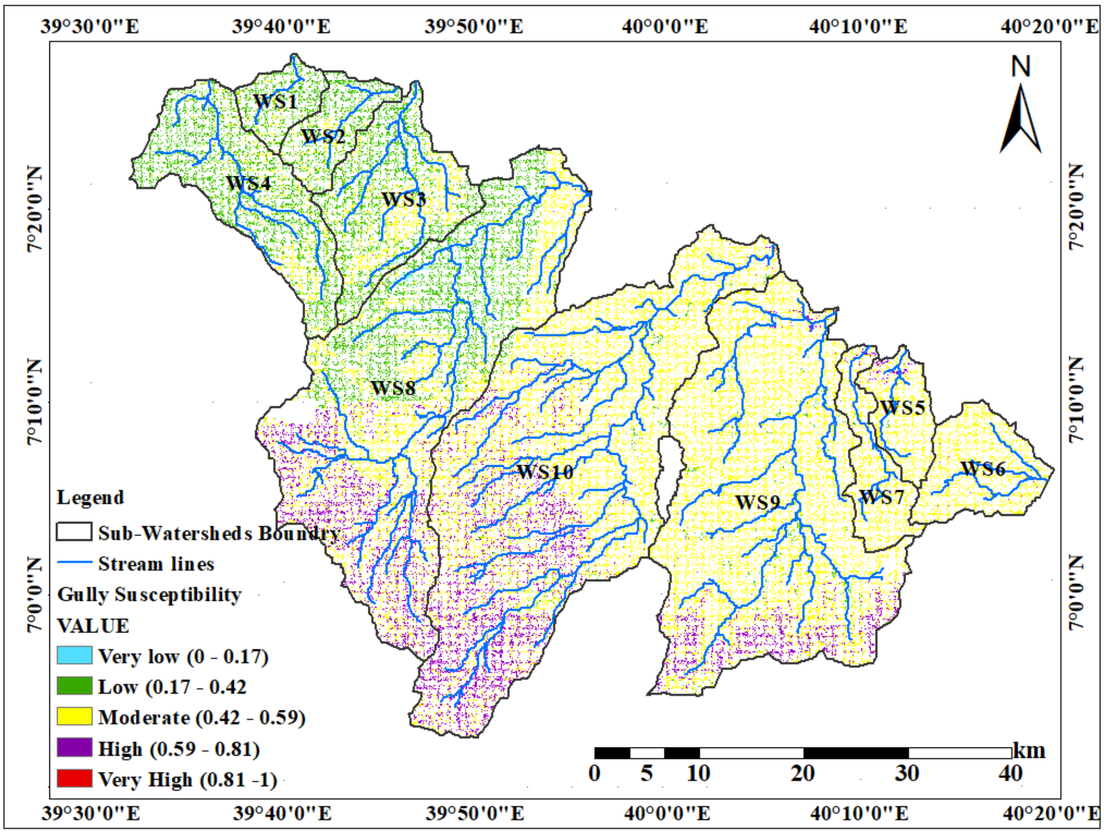

Figure 7. Gully erosion susceptibility map of the watershed

Validation of Gully Susceptibility Map

The predictive accuracy of the gully susceptibility model was validated using 30 GPS-mapped gully head locations collected during field surveys. The inventory points were imported into ArcGIS (WGS-84) and overlaid on the susceptibility raster, and the extract Values to Points tool was used to assign each gully the corresponding susceptibility class (very low-very high). The results show strong agreement between predicted and observed gully distribution, where 50% of the gullies occur in high and very high classes and about 80% fall within moderate to very high zones, confirming the robustness of the weighted overlay model and its ability to capture key geomorphological drivers such as slope, drainage concentration, and runoff accumulation.

The spatial pattern is further supported by the sub-watershed (WS) analysis, where higher gully densities occur in WS8-WS10, characterized by steep slopes and high drainage density, while WS1-WS4 contain fewer gullies and correspond mainly to low -moderate susceptibility zones; WS5-WS7 represent transitional conditions. This indicates that the majority of gully occurrences fall within predicted erosion-prone areas, confirming the reliability of the susceptibility model. The model accurately captured the key geomorphological drivers of gully formation, with an R^2 of ~0.75, demonstrating strong predictive performance (Table 11 and Figure 8). This confirms that the GIS-based MCDA (AHP) approach provides a robust basis for prioritizing watershed interventions and guiding targeted soil and water conservation measures.

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**

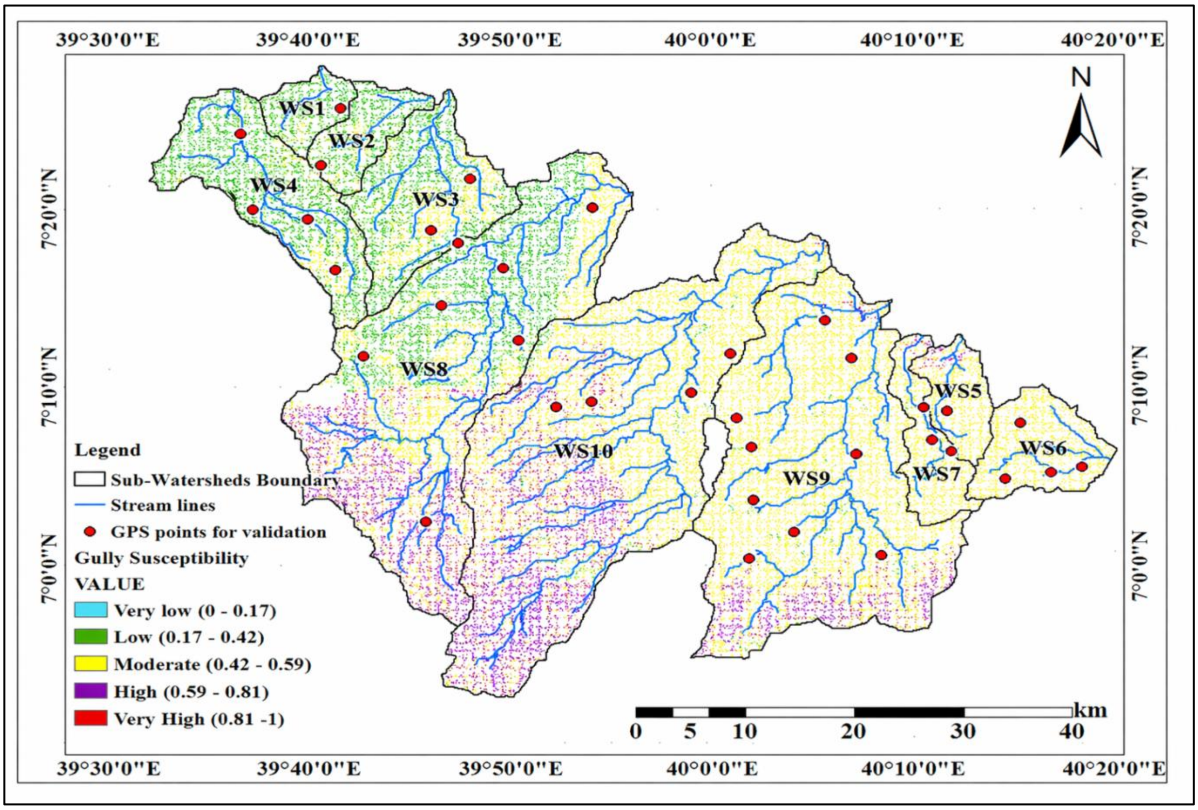

Figure 8. Validated gully erosion susceptibility map of the watershed

Conclusion and Recommendation

Conclusion

In conclusion of this study, the integration of geospatial techniques with Multi-Criteria Decision Analysis using the Analytic Hierarchy Process proved to be an effective and reliable approach for assessing and mapping gully erosion susceptibility in the Bale Highlands. The findings revealed that gully erosion is governed by a complex interaction of environmental and anthropogenic factors, with rainfall and land use/land cover identified as the dominant drivers, followed by slope and topographic wetness index.

The spatial analysis showed that moderate to high susceptibility zones are primarily concentrated in areas characterized by steep slopes, high rainfall, cultivated land, and strong hydrological connectivity. The validation results demonstrated strong agreement between predicted susceptibility and observed gully locations, confirming the robustness of the model in identifying erosion-prone areas. This study provides a clear and scientifically grounded understanding of the spatial distribution and controlling factors of gully erosion, highlighting the critical importance of spatially explicit tools for informed decision making in soil and water conservation planning. Overall, the findings significantly contribute to advancing sustainable land management practices and reducing land degradation in erosion-vulnerable highland regions.

Recommendations

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.

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