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Susceptibility, change and drivers of riverine gullies in an Afromontane agroecosystem

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Abstract
Riverine gully erosion threatens agricultural productivity, infrastructure, water resources, and livelihoods in steep tropical agroecosystems, yet catchment-scale evidence that integrates field-measured gully morphology, susceptibility modelling, temporal change, and community-perceived drivers remains limited This study assessed the susceptibility, distribution of severity, change, and community-perceived drivers of riverine gully erosion in the Lwakhakha sub-catchment of eastern Uganda. The geometries of 25 gullies were measured using Real-Time Kinematic (RTK) positioning, and geocoded gully locations were integrated with soil characteristics, slope, elevation, geology, rainfall, and Normalised Difference Vegetation Index (NDVI) datasets. A total of 380 households were randomly selected and interviewed using semi-structured questionnaires. The results of this study revealed that gully erosion occurred across three severity classes (high, moderate, and low), with gullies occupying a total area and volume of 209,116 m^2 and 260 m, respectively. The best predictors of riverine gully erosion were slope, elevation, and NDVI. Changes in gully erosion indicated that gullies are actively increasing in both area and volume, and the perceived major drivers were slope steepness, erratic rainfall, soil type, weak underlying geology, absence of vegetation cover, deforestation, poorly constructed roads, and the land tenure system ($P < 0.05$). Community responses identified interacting physical, economic, and social drivers, particularly slope steepness, intense rainfall, soil and geological conditions, vegetation loss, deforestation, road drainage, poverty, and land-tenure constraints. The combined evidence indicates that gully erosion in the Lwakhakha sub-catchment is a coupled hydro-geomorphic and socio-environmental process. Interventions should therefore prioritise the upper and middle sub-catchments and combine runoff control, vegetation restoration, road drainage management, sustainable land management, and locally appropriate livelihood and tenure measures.

Keywords Gully geometry · Random forest model · Multinomial model · Mt Elgon · Lwakhakha

1 Introduction

Globally, riverine gully erosion poses a significant risk to agroecosystems, critical 12facilities, and infrastructure [21]. It develops where concentrated surface or subsurface flow exceeds the resistance of soil and underlying materials, producing incised channels that can progressively enlarge to form gullies [41]. Gullies are commonly

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categorised into permanent and ephemeral forms. Permanent gullies are generally too large to be removed by conventional tillage, whereas ephemeral gullies are smaller channels formed by concentrated flow that may be temporarily obliterated by normal cultivation [45]. Permanent gullies are commonly described as erosion channels with a depth of 0.5–30 m or a cross-sectional area larger than 0.09 m^2 that cannot be obliterated by conventional tillage due to their large size. This distinction is important because persistent riverine gullies can evolve into long-lived sediment sources and hydrological conduits that connect hillslopes directly to stream networks. The development of gully erosion can occur in two stages, as it can be initiated by various mechanisms, e.g., cutting, penetration or piping, tension gap progression and terminate with subsurface instability leading to scattering and collapse of its margins [4]

Gullies are increasingly threatening agricultural investments, water-resource integrity, infrastructure, and household food security [53]. Their initiation and expansion reflect interactions among natural controls, including rainfall, soil and geological properties, topography, drainage convergence, and vegetation cover, and anthropogenic pressures such as cultivation, deforestation, road construction, and settlement. When runoff carves and sediment is transferred, it causes siltation and aggradation in river channels. As a result, it exposes tree roots and damages water-supply infrastructure and agricultural land [8, 24]. Over the last 2000 years, particularly during the last 300 years, these impacts have been particularly acute in mountainous environments, where steep slopes, high rainfall intensity, and strong hillslope-channel connectivity amplify hydro-geomorphic responses to livelihoods and exert increasing influence on catchments and their watercourses [13]. Riverine gully erosion undermines progress towards achieving Sustainable Development Goals (SDGs), specifically SDGs 2 (Zero hunger), 6 (Clean water and sanitation), 13 (Climate action), 14 (Life below water) and 15 (Life on land) [40]. The communities are more food and water insecure due to losses and damages caused by gully erosion [65].

Riverine gully erosion is a significant form of soil erosion that contributes substantially to soil degradation [41]. Furthermore, active gullies are not only an important source of sediment but also serve as a pathway for runoff and sediment [25]. Over time, spatial technologies have been deployed to monitor gully development and associated impacts on landscapes. Satellite images (visible, infrared and microwave bands), or combinations thereof, have been successfully used to discriminate and delineate gully types [80]. Accurate mapping of gully form is therefore a necessary precondition for understanding and managing these systems [20]. However, the effectiveness of gully erosion susceptibility assessment via GIS depends on the appropriate selection of conditioning factors that play an important role in gully erosion [54].

Previous gully-erosion research has advanced several complementary approaches, including GIS-based mapping and quantification [42], severity mapping using multi-criteria techniques [63], geomorphological susceptibility assessment [18], and spatial modelling using statistical and machine-learning methods [70, 77]. However, these strands of evidence are often analysed separately. Fewer studies integrate repeated in-situ measurements of gully geometry with catchment-scale susceptibility modelling and local knowledge of the socio-economic and infrastructural processes that condition gully development. This integration is particularly important in data-scarce tropical mountain agroecosystems, where field measurements can constrain remote sensing and GIS interpretations, and community evidence can reveal drivers not represented in environmental raster datasets. In the Lwakhakha sub-catchment, existing studies have addressed agricultural practices and soil and water conservation [48], land-cover change [14], and rainfall-runoff modelling [47], but catchment-scale evidence linking riverine gully morphology, susceptibility, temporal expansion, and perceived drivers remains limited. This study addresses that gap using an integrated field, geospatial, statistical, and socio-economic framework.

Therefore, this study assessed the spatial riverine gully geometries, susceptibility, temporal changes, and the perceived drivers of riverine gully erosion in the Lwakhakha sub-catchment. The objectives of this study were 1) to characterise the morphology-based severity of measured riverine gullies and their catchment-scale susceptibility, 2) quantify changes in gully morphology between 2023 and 2025, and 3) to identify physical, economic, and social drivers perceived by communities and local technical stakeholders. Therefore, by integrating measured gully geometry with environmental predictors and local knowledge, the study provides evidence for spatial

prioritisation of gully stabilisation, integrated water-resources management, sustainable land management, infrastructure planning, and locally grounded catchment management.

2 Materials and methods

2.1 Description of study area

The study was conducted in Lwakhakha sub-catchment on the slopes of Mt. Elgon. The area lies between latitudes 0° 34′ 26″ N and 1° 8′ 0″ N and longitudes 33° 53′ 48″ E and 34° 32′ 26″ E (Fig. 1). The sub-catchment is transboundary, shared between Uganda and Kenya, and covers approximately 586 square kilometres. This study focused on the Uganda border side due to resource constraints. The sub-catchment covers approximately 329.7 square kilometres of land area across the districts of Namisindwa (57.9%), Manafwa (21%), and Tororo (18.7%).

The Lwakhakha sub-catchment experiences a tropical climate with a bimodal rainfall pattern, with average annual rainfall ranging from 1290 to 1980 mm. The sub-catchment exhibits significant differences in the spatial and temporal distributions of rainfall depth and intensity due to orographic influence and altitude. Mt. Elgon stands at 4322 m above sea level, with a topography characterised by numerous hills and ranges that act as micro-catchment areas for rivers radiating out from the Mountain. The River Lwakhakha sub-catchment is the largest on the mountain, with tributaries such as Laaso and Taaso, Namunyiri, Namikhoma, Ririma, and Kodike, which converge to form River Malaba in the lower catchment, and subsequently drains into Lake Kyoga via River Mpologoma. The topographic attributes of Mt Elgon, coupled with heavy rains during the two main seasons, accelerate soil erosion and other landscape processes, forming deep riverine gullies (Fig. 2). The sub-catchment is overlaid with volcanic soils in the upper part, moderately deep to very deep, well-drained, reddish-brown to yellow–brown, friable clay soils in the middle catchment; imperfectly drained to poorly drained, friable sandy clay loam soils in the river valleys; and hydromorphic alluvial sand deposits in the floodplain.

The sub-catchment's vegetation varies with altitude and micro-climate conditions. Tropical grassland savannah transitions into tropical forest, then montane vegetation, from the bottom towards Mt Elgon's summit. Due to

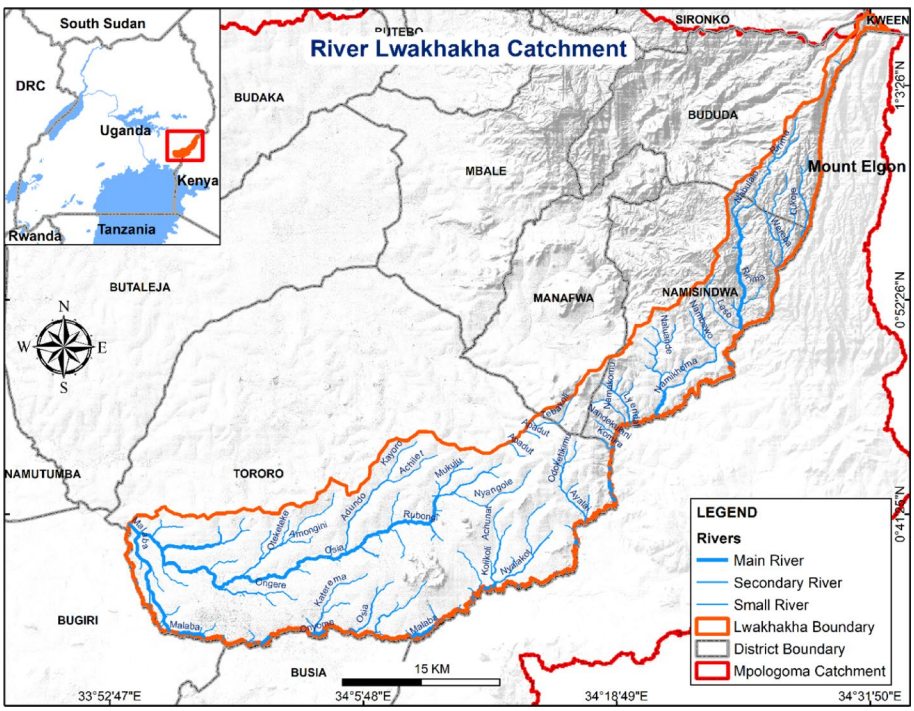


Fig. 1 Location of the study area



Fig. 2 Gully in Bumwoni sub-county, Namisindwa District

population pressure, the natural vegetation here has been extensively transformed, especially in the middle and lower reaches of the catchment, exacerbating riverine gully erosion. Subsistence agriculture is the primary source of livelihood in the Mt. Elgon area, including the Lwakhakha sub-catchment. However, agricultural productivity has been declining in the recent decades5 due to reduced land productivity, occasioned by declining soil nutrient levels, which is also related to soil erosion and landslide occurrence [32].

The road network in Lwakhakha sub-catchment contributes to concentrated surface runoff along Lwakhakha Highway, which increases flow velocity and soil detachment on adjacent slopes. This initiates gullies new gullies along the highway as well as widening already created channels.

2.2 Riverine gully geometry assessment

2.2.1 Approach

A sub-catchment approach was adopted to investigate the distribution and susceptibility of gully erosion in riverine gullies. The gullies were mapped across the three sections of the sub-catchment (Upper, Mid and Lower) to capture their spatial distribution and assess their morphological changes and development. Administratively, the gullies were monitored in the sub-counties of Kwapa (Tororo District—lower section), Bunyinza and Bubutu (Manafwa District—middle section), and Bumwon and Bukiabi (Namisindwa District—upper section). These sub-counties were selected based on the observed severity, gully development, and distribution following a reconnaissance (2022) study and consultations with local leaders and farmers adjacent to the riverbank. During the reconnaissance, an observation checklist was used to assess the condition of gullies and the stabilisation technologies being applied.

2.2.2 Data collection and tools

The datasets used to characterise the spatial distribution of riverine gullies included gully geometry, administrative boundaries, and the sub-catchment boundary. Administrative boundary data (2022) were generated from the Uganda Bureau of Statistics, while the sub-catchment boundary was delineated using Shuttle Radar Topography Mission (30 m) data.

Repeated gully-geometry measurements were undertaken at the same monitoring locations in May 2023 and November 2025, representing the end of the first and second rainy seasons, respectively. A Real-Time Kinematic (RTK) GNSS receiver (T300 SINO, configured to the Eagle CORS network) was used to improve positional

accuracy during field mapping, consistent with its application in monitoring gully development [67, 68]. Because the two surveys were conducted in different rainy seasons, seasonal hydrological conditions should be considered when interpreting the measured temporal differences.

Much as a series of studies [19, 39, 69] have mapped gully geometries in mountainous landscapes, there are few studies [36] that have been conducted at the catchment level in mountainous agroecosystems in the tropics. The studied landscape is characterised by smallholder farming systems in which individual farms are less than 0.5 acres in size,there is high dependence on rainfed agriculture and widespread use of family labour in crop production. The gully geometry data (depth, width, length were collected in the identified reach area along the river channel. Out of 60 gullies identified during the reconnaissance phase, 25 gullies were measured in the field using the same monitoring points for the period of study. At each sampling point, 5 points were selected at 100-m intervals along the river channel and measured. The 100-m interval was sufficient given the ruggedness of the landscapes and the patchiness of channel-bank land-use types. The mapped gullies were selected based on their locations within agricultural land-use types. The gully field data were collected using a handheld Global Positioning System (GPS, Garmin 64s, ± 4 m and a Real-Time Kinematic (RTK machine. A 50 m measuring tape was also used for verification purposes.

2.2.3 Data analysis

Field and monitoring-site data were collated and quality-checked in Microsoft Excel before statistical analysis. Gully planform area was estimated from measured length and representative width, while gully volume was estimated from length, width, and depth measurements. These geometric estimates are proxies for gully dimensions rather than direct measurements of eroded sediment mass and consequently, area and volume should not be interpreted as soil-loss rates unless bulk density and an explicit temporal conversion are applied. Descriptive statistics (mean, standard deviation, minimum, maximum, and sum, where appropriate) were used to summarise gully length, depth, width, area, and volume. Gully morphology was compared across monitoring periods to characterise changes in channel dimensions and development [71].

Descriptive statistics were computed for gully length, depth, width, area, and volume. Partitioning Around Medoids (PAM) were then used to group the field-measured gullies into morphology-based clusters using gully area and volume, resulting in low-, moderate-, and high-severity classes. One-way Analysis of Variance (ANOVA) was used to test whether gully geometry differed among these severity classes, with post-hoc group lettering reported in Table 1. Spatial predictor datasets were georeferenced and resampled to a common 10-m grid referenced to Sentinel-2 imagery. A paired-samples t-test was used to compare repeated measurements of gully length, depth, width, area, and volume between 2023 and 2025, with statistical significance evaluated at $\alpha = 0.05$.

Multinomial logistic regression model [38] was used to examine associations between environmental factors and the four gully classes.

Let Y denote gully class and let the erosion-free class be the reference category. Performed to investigate the effect of on gully severity categories. Gully severity classes (low, moderate, and high) formed the dependent variable, while geology category (sedimentary/free), slope class (low, moderate, high/free), rainfall intensity (low, moderate, high/free), and NDVI levels (low, moderate, high/free) formed the independent variables. The low severity category was used as the reference group, and results were presented as relative risk ratios to estimate the likelihood of higher severity levels relative to the baseline category (Agresti, 2013). Results from this model were used as input to the Random Forest (RF) model to predict gully erosion susceptibility, from which a gully erosion susceptibility map for the Lwakhakha sub-catchment was produced.

Table 1 Riverine gully geometry characteristics

Statistics	Length (m)	Depth (m)	Width (m)	Area (m^2)	Volume (m^3)
Mean	1354.0	1.7	5.9	8364.6	10.4
SD	841.3	0.6	2.4	7300.5	6.4
Sum	33850	42	147	209116	260

2.3 Susceptibility of riverine gully erosion

2.3.1 Datasets and sources

A holistic hotspot approach was used to assess the sub-catchment's susceptibility to gully erosion. The datasets used to estimate areas prone to gullies include soil, topography, rainfall, and vegetation. The topography data (slope and elevation) were obtained from a 30-m Shuttle Radar Topographic Mission Digital Elevation Model covering the study area, downloaded from the USGS GeoPortal (https://glovis.usgs.gov/) in its native format and later reprojected to a UTM N36 coordinate system. Land use/cover data (2024) were obtained from the Uganda National Forestry Authority. The key patched land-use/cover types were farmland, built-up areas, tree plantations, and bushlands. Rainfall data were sourced from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) website (https://chc.ucsb.edu/data/chirps).

Soil texture data (2009) were obtained from the Uganda National Agricultural Organisation, while geological data (2000) were obtained from the Department of Geological Survey and Mines, Uganda. Vegetation data (2023) were extracted from the Red and Infrared bands of a Sentinel-2 (10m) image downloaded from the European Space Agency's Copernicus Data Space (https://browser.dataspace.copernicus.eu/). The image analysed was taken during the dry season (January), when cloud cover did not compromise image quality. NDV was computed from the Red and Infrared Bands in ArcGIS 10.8 using the formula below.

$$\mathrm{NDVI} = \frac{(Near\ Infrared\,(\mathrm{B8}) - \mathrm{Red}\,(\mathrm{B4}))}{(Near\ Infrared\,(\mathrm{B8}) + \mathrm{Red}\,(\mathrm{B4}))} \quad (1)$$

There are no rules governing the use of Gully Erosion Conditioning Factors (GECFs). Huang et al. (2022) noted that factors influencing gully formation may differ from one environment to another. The spatial datasets were pre-processed by resampling them to 10m spatial resolution to facilitate spatial statistical computations.

Multicollinearity is a situation in which two or more predictor variables in a multiple regression model are strongly related to one another. In this study, the Tolerance (TOL) and its reciprocal, the variance inflation factor (VIF), were used to assess multicollinearity (Senaviratna and Cooray, 2019). As a rule of thumb, a TOL < 0.2 or a VIF > 5 indicates that variables have collinearity problems (Daoud, 2018). To add to the multicollinearity test using VIF and TOL, the outcome from the Pearson correlation matrix [3], was also revealed. The general rule of thumb for the Pearson correlation coefficient is that if the correlation coefficient between two variables is greater than 0.9, multicollinearity is a serious problem where r (Pearson correlation) = 1, shows a strong perfect positive correlation thus a perfect linear relationship where both variables increase together proportionally just like where r = − 1, shows a strong perfect negative correlation where one variable increases while the other decreases proportionally. GECFs with evidence of collinearity were eliminated. VIF values ranged from 0.00 to 35.987, while TOL values (the reciprocal of VIF, as noted by [3]) ranged from 0.00 to 0.900. Typically, TOL < 0.2 or VIF > 5 indicates collinearity issues (Daoud, 2018).

2.3.2 Random forest model

The Random Forest (RF) model is a supervised machine learning algorithm applicable to both classification and regression tasks. RF works by building multiple decision trees using independently selected samples and randomly drawing trees from the same distribution within the forest [12]. This model can predict the distribution of gully erosion risk in mountainous ecosystems [15]. The Random Forest (RF) model was run in the R-4.4.2 statistical software environment and RStudio-2024.09.1-394. To implement the model, a shapefile containing geolocation data for the derived gully erosion classes was prepared for model training, and a composited raster file containing predictor variables was also prepared in ArcGIS 10.8.

To limit overfitting [59], 70% was allocated to model training and 30% to validation [10]. Predictor importance was evaluated using Mean Decrease Accuracy (MDA) and Mean Decrease Gini (MDG).

To limit overfitting [59], 70% of the observations were allocated to model training, while 30% were allocated to validation [10]. Predictor importance was evaluated using the Mean Decrease Accuracy (MDA) and Mean Decrease Gini (MDG), where larger values indicate greater contributions to predictive performance or node purity [28, 59]. This is because the gully observations are spatially structured,a random train-validation split may therefore yield optimistic accuracy if nearby observations occur in both subsets. Also, the applications should consider spatial block or spatial cross-validation to test model transferability across independent parts of the studied catchment.

The model was evaluated using the Area Under the Receiver Operating Characteristic (ROC) Curve (AUC). The area under the ROC curve (AUC) is widely recognised as the measure of a diagnostic test's discriminatory power (Fan et al., 2006). ROC curve is the plot that depicts the trade-off between sensitivity and (1-specificity) across a series of cut-off points (Kumar and Indrayan, 2011). Sensitivity and specificity are two measures of the inherent validity of a diagnostic test (Kumar and Indrayan, 2011). AUC values of 0.5–0.6, 0.6–0.7, 0.7–0.8, 0.8–0.9, and 0.9–1.0 were used as thresholds, with test values classified as unsatisfactory, satisfactory, good, very good, and excellent, respectively (Trifonova et al., 2014). The training dataset (70%) was used to predict the spatial susceptibility to gully erosion [58]. The susceptibility map was developed with 4 classes: Free, Low, Moderate, and High, in line with the gully erosion susceptibility [58]. The validation data (30%) and the gully erosion model built were used to validate the susceptibility map in R. The AUC–ROC was plotted using the pROC and caret libraries.

2.4 Perceived drivers of riverine gully erosion in Lwakhakha sub catchment

Socio-economic datasets were collected and analysed to characterise the underlying drivers of gully erosion in the sub-catchment. Primary socio-economic data were collected from smallholder farmers, community leaders, and technical officers (from the natural resources and agricultural departments) responsible for the sub-catchment. Socio-economic data have been widely collected and interpreted to inform the drivers of gully erosion [17, 29, 30]. This study focused on smallholder farmers in the sub-counties adjacent to gully channels. The drivers of gully erosion were classified into three categories i.e., physical (slope steepness, intense rainfall, soil characteristics, surface water movement, underlying geology, vegetation cover, and runoff from steep ground), economic (deforestation, road construction, farming, house construction, and land management) and social (poverty, land tenure, population pressure, land cover change, and traditional land practices).

The smallholder farmers cultivating adjacent to the gullies were targeted in this study. A multistage sampling design was adopted to select the respondents. In the first phase, the districts (Manafwa, Tororo, and Namisindwa) that cover the sub-catchment were selected. In the second phase, sub-counties and parishes overlying the gullies were purposively chosen. In the last phase, the adjacent villages were also purposively selected and studied. At the village level, the smallholder farmers were randomly selected using village registration forms for interviews. In Tororo District, the selected sub-counties were Kwapa (lower section), Manafwa (Bunyinza and Bubutu—middle section), and Namisindwa (Bumwon and Bukiabi—upper section). A total of 380 households were selected and interviewed. The sample size was determined from a population of 24,842 households in the sub-catchment (UBOS, 2024) using Krejcie and Morgan's (1970) sample size determination procedure (Eq. 2).

The sample size was computed using the formula below:

$$S = \frac{X^2 * N * P\,(1-P)}{d^2\,(N-1) + X^2 * P(1-P)} \tag{2}$$

where: S = required sample size; N = population size = 24,842; P = population proportion (assumed 0.5 for maximum sample size); d = degree of accuracy (0.05); and X^2 = chi-square value at 95% confidence = 3.841.

$$S = \frac{3.841 * 24842 * 0.5\,(1-0.5)}{0.05^2\,(24842-1) + 3.841 * 0.5(1-0.5)} \approx 380 \tag{3}$$

The final sample size of household respondents was scaled down to 329. This was attributed to data cleaning and non-response from some of the intended respondents, which led to the exclusion of incomplete response records. This sample size was sufficient to attain the study's statistical power. Socio-economic datasets were collected through a household survey, Key Informant Interviews (KIIs), and Focus Group Discussions. A semi-structured questionnaire was developed and pretested to collect data on the drivers of gully erosion. An interview guide was developed and used to collect data on the drivers of gully erosion from five key informants (natural and agricultural officers). Five Focus Group Discussions comprising 20 participants were also conducted in the selected sub-counties. The pretested semi-structured questionnaires were administered by five trained research assistants with bachelor's-level academic qualifications who were conversant with the terrain and local language (Lumasaba) because they were residing in the study area. These interviews were conducted in the participants' localities and lasted between 1 and 2 h. The research assistants administered the tools coded in KoboCollect.

2.5 Data analysis

A Chi-Square (X^2) test was applied to the quantitative data to identify the drivers of gully erosion across the different sections of the sub-catchment (upper, middle, and lower). The X^2 is determined by comparing observed and expected frequencies, with the expected frequencies obtained by multiplying the sample size by the probability that an element belongs to a given class (Prem and Mann, 2012). The Chi-square test is calculated as shown in Eq. (4) below.

$$X^2 = \sum \frac{(0-E)^2}{E} \tag{4}$$

where;

0 = observed frequency for a class, E = expected frequency for a class.

2.6 Multinomial logit model specification

Let the outcome variable, the gully erosion classes be:

$$Y_i \in \{Low, Moderate, High, Free\} \tag{5}$$

and let the explanatory variables be geology category, slope, rainfall, and NDVI. The probability that observation belongs to category j can be written as:

$$P(Y_i = j \mid X_i) = \frac{exp\left(Xi'\beta_j\right)}{\sum_{k=1}^{j} exp(Xi'\beta_k)} \tag{6}$$

where $j = 1,2,3,4$ represents the gully classes of Low, Moderate, High, and Free, respectively.

Substituting the study variables into Eq. (6), the multinomial logistic regression model is specified as follows:"

$$P\left(Y_i = j|X_i\right) = \frac{exp\left(\beta_{0j} + \beta_{1j}GEO_i + \beta_{2j}SLOPE_i + \beta_{3j}RAIN_i + \beta_{4j}NDVI_i\right)}{\sum_{k=1}^{4} exp\left(\beta_{0k} + \beta_{1k}GEO_i + \beta_{2k}SLOPE_i + \beta_{3k}RAIN_i + \beta_{4k}NDVI_i\right)} \tag{7}$$

where GEO_i represents geology category, $SLOPE_i$ represents slope, $RAIN_i$ represents rainfall, and $NDVI_i$ represents the normalized difference vegetation index.

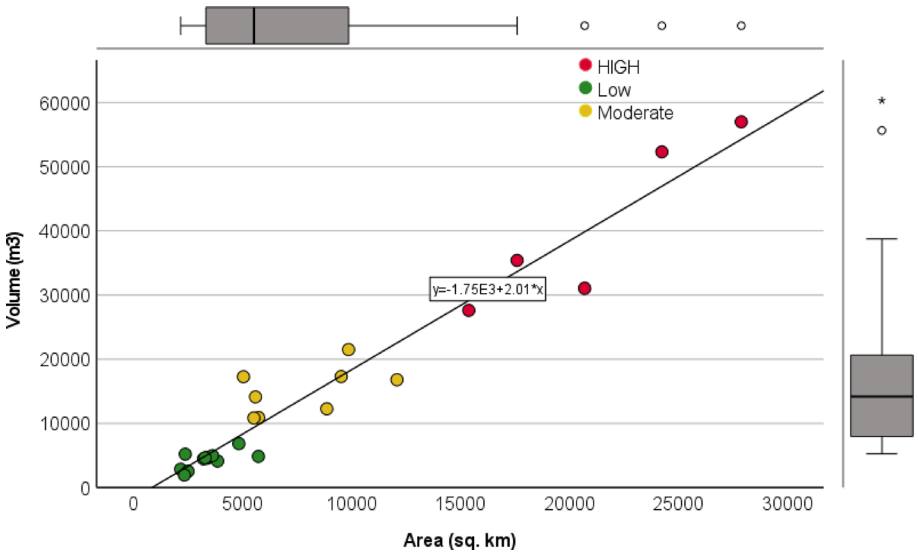


Fig. 3 Relationship between area and volume by Erosion severity (Scatter plot)

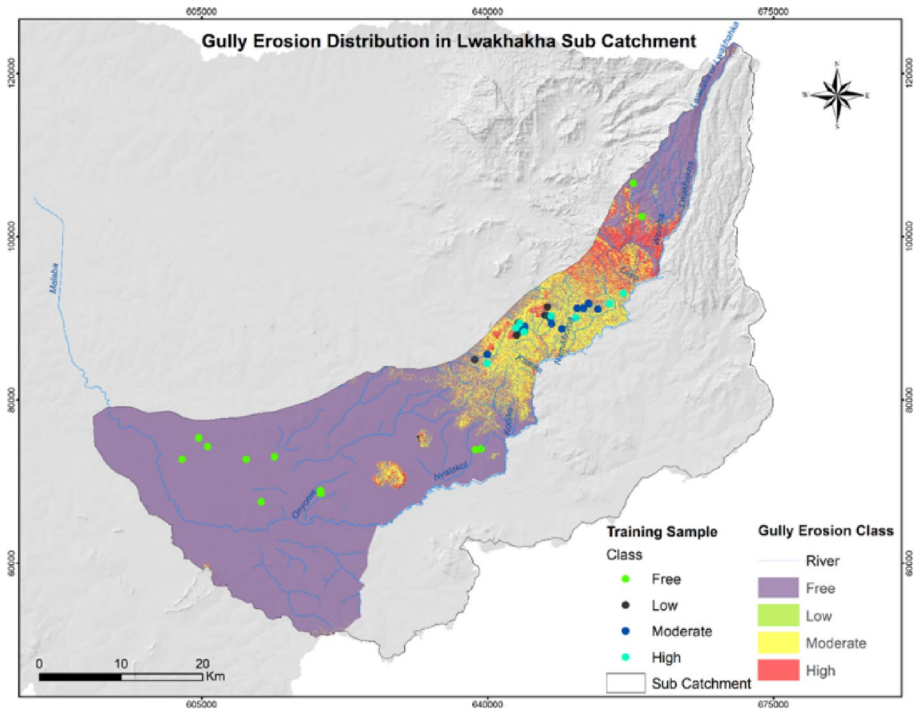


Fig. 4 Gully Erosion Susceptibility

3 Results

3.1 Susceptibility of riverine gully erosion in Lwakhakha sub-catchment

Across the 25 measured gullies, the mean length was 1354.0 m (SD = 841.3 m), and the total mapped length was 33,850 m. Mean depth was 1.7 m (SD = 0.6 m), and mean width was 5.9 m (SD = 2.4 m). Total mapped planform area was 209,116 m^2 (20.91 ha), with a mean of 8364.6 m^2 per gully. The shortest gully (500 m) occurred at Ochegen Ward, Kwapa Town Council, Tororo District, whereas the longest (3860 m) was recorded at Nabitsikhi Village, Bunyinza Sub-County, Manafwa District (Figs. 3 and 4).

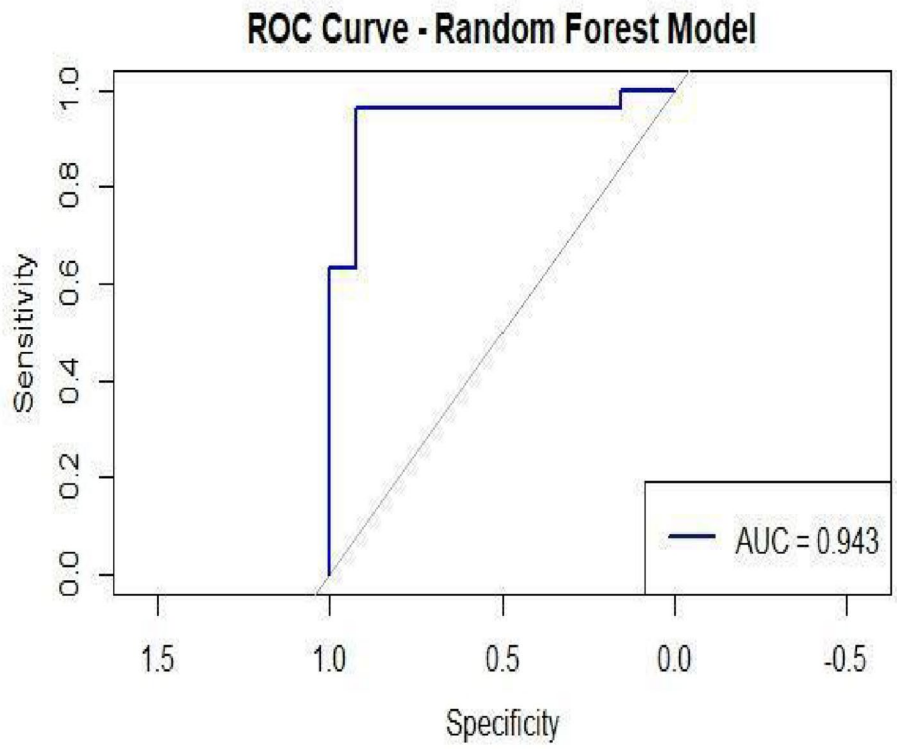


Fig. 5 Receiver operating curve for random forest model with associated AUC values

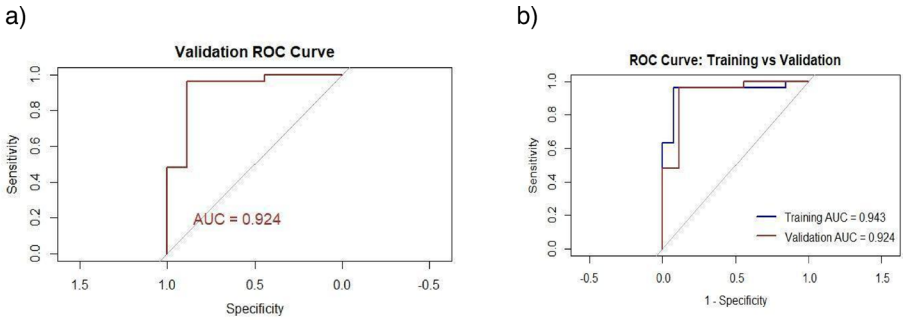


Fig. 6 The receiver operating characteristic curve with AUC for susceptibility map (**a**), validation and ROC with associated AUC for model training and validation (**b**)

PAM results revealed three clusters of gully sizes: small, medium, and large (Fig. 5). The scatter plot shows a linear relationship between gully area and volume, implying that gully volume increases with gully area.

The Random Forest (RF) model classified the sub-catchment into four susceptibility categories: free, low, moderate, and high (Table 3; Fig. 6). The moderate susceptibility class occupied 132 km^2 (39%), followed by the free 104 km^2 (31%), high 78 km^2 (24%) and low 19 km^2 (6%). Thus, approximately 63% of the mapped sub-catchment fell within moderate- or high-susceptibility classes, indicating a substantial spatial concentration of potentially unstable terrain. Slope, elevation, and NDVI are ranked as the major predictors in the fitted model. This ranking does not imply that rainfall, soil, or geology are unimportant but rather, it indicates that slope, elevation, and NDVI contributed more strongly to prediction within the specific dataset and model configuration. Model performance was high (AUC = 0.943), with an OOB error rate of 7.53%, although the form of multiclass AUC calculation should be specified (Fig. 7).

An assessment of accuracy using AUC values was classified as: poor (0.5–0.6), moderate (0.6–0.7), good (0.7–0.8), very good (0.8–0.9), and excellent (0.9–1.0) [45] (Fig. 10). The model provided an excellent AUC value of 0.943. The OOB estimate of the error rate achieved was 7.53% (Fig. 10).



Fig. 7 Arrow points to a spring in Bubutu sub-county threatened by an expanding gully, Namisindwa District

Table 2 Random forest model (RFM) results

Gully erosion classes	Area (sq.km)	Percentage (%)
Free	104	31
Low	19	6
Moderate	132	39
High	78	24

3.2 Relationship between riverine gully geometry (length, width, depth and area) and gully erosion severity (low–high)

In Table 1, the mean gully length was greatest in the high-severity class (2.71 ± 0.79 km; F = 23.85, $P = 0.001$). Mean depth was greatest in the moderate class (2.07 ± 0.66 m; F = 7.53, $P = 0.032$), while mean width was similarly high in the moderate and high classes (7.34 ± 1.74 and 7.97 ± 1.15 m, respectively; F = 15.60, $P = 0.001$). Gully area increased strongly across the three classes, from 3405.96 ± 1058.46 m^2 in the low class to 21,168.81 ± 5021.75 m^2 in the high class (F = 75.97, $P = 0.001$). These results indicate that severity is expressed through multiple dimensions of channel enlargement rather than through depth alone (Tables 2 and 3).

These results imply that the high severity class had the longest gullies compared to the low and moderate classes, while gullies in the moderate class presented higher gully depth compared to those in the lower and higher severity classes. On the other hand, gully width was higher in the moderate and high classes than in the lower class. In terms of area, the results indicate that larger gully areas are associated with greater gully erosion severity in the catchment. Gullies were mostly concentrated on the middle and upper reaches of the sub-catchment, mainly in Namisindwa District (Fig. 3).

Table 3 Relationship between riverine gully geometry (length, width, depth and area) and gully erosion severity

SD Standard Deviation

Variable	Low	Moderate	High	F-value	*P*-value
	Mean ± SD	Mean ± SD	Mean+SD		
Gully length (km)	0.97 ± 0.45[b]	1.08 ± 0.30[b]	2.71 ± 0.79[a]	23.85	0.001
Gully length (m)	967.50 ± 451.85[b]	1083.75 ± 303.03[b]	2714.00 ± 786.18[a]	23.85	0.001
Gully depth (m)	1.30 ± 0.35[b]	2.07 ± 0.66[a]	1.90 ± 0.26[ab]	7.53	0.032
Gully width (m)	4.02 ± 1.66[b]	7.34 ± 1.74[a]	7.97 ± 1.15[a]	15.60	0.001
Area (m^2)	3405.96 ± 1058.46[c]	7800.02 ± 2634.63[b]	21,168.81 ± 5021.75[a]	75.97	0.001

Table 4 The marginal effects of the multinomial model

Variable	Category	dy/dx	Std. Err	z	*P*-value	95% CI
Geology category						
Sedimentary	Low	0.322	0.113	2.86	0.004**	[0.10, 0.54]
	Moderate	0.253	0.057	4.42	<0.001***	[0.14, 0.37]
	High	0.145	0.092	1.58	0.115	[0.04, 0.33]
	Free	−0.72	0.159	−4.52	<0.001***	[−1.03, −0.41]
Slope	Low	0.024	0.012	2.03	0.043**	[0.00, 0.05]
	Moderate	0.047	0.013	3.63	<0.001***	[0.02, 0.07]
	High	0.024	0.021	1.12	0.261	[−0.02, 0.06]
	Free	−0.094	0.02	−4.66	<0.001***	[−0.13, −0.05]
Rainfall	Low	0.002	0.004	0.4	0.689	[−0.01, 0.01]
	Moderate	0.011	0.004	2.47	0.014**	[0.00, 0.02]
	High	0.004	0.006	0.76	0.45	[−0.01, 0.02]
	Free	−0.017	0.005	−3.07	0.002**	[−0.03, −0.01]
NDVI	Low	0.141	0.239	0.59	0.555	[−0.33, 0.61]
	Moderate	0.638	0.239	2.67	0.008**	[0.17, 1.11]
	High	0.279	0.345	0.81	0.419	[−0.40, 0.96]
	Free	−1.058	0.319	−3.32	0.001**	[−1.68, −0.43]

less than %%; * less than 1%

3.3 Relationship between major gully drivers and gully erosion classes

The multinomial model identified statistically significant associations between several environmental predictors and the probability of different gully classes (Table 4). Sedimentary geology was associated with higher predicted probabilities of the low and moderate classes (average marginal effects = 0.322 and 0.253, respectively) and a lower probability of the erosion-free class (−0.720). Slope showed smaller but significant positive marginal effects for the low (0.024) and moderate (0.047) classes and a negative effect for the erosion-free class (−0.094). Rainfall was significantly associated with the moderate class (0.011) and inversely associated with the erosion-free class (−0.017), while its effects on low and high classes were not statistically significant. NDVI had a positive marginal effect for the moderate class (0.638) and a negative marginal effect for the erosion-free class (−1.058), with non-significant effects for low and high classes. These coefficients should be interpreted as derivatives of predicted class probability with respect to a one-unit change in the predictor; for continuous variables such as NDVI, reporting effects for a realistic increment (for example, 0.1 NDVI units) would provide a more intuitive ecological interpretation.

The multinomial model identified statistically significant associations between several environmental predictors and the probability of different gully classes (Table 4). The marginal effects analysis reveals several key insights into the relationships among geology, slope, rainfall, and NDVI (Normalised Difference Vegetation Index) and the predicted outcomes (Table 4). Specifically, sedimentary geology was associated with higher predicted probabilities for the low and moderate classes (average marginal effects of 0.322 and 0.253, respectively) and a lower probability for the erosion-free class (−0.720). Slope showed smaller but significant positive marginal effects for the low (0.024) and moderate (0.047) classes and a negative effect for the erosion-free class (−0.094).

Rainfall was significantly associated with the moderate class (0.011) and inversely associated with the erosion-free class (−0.017), while its effects on low and high classes were not statistically significant. NDVI had a positive marginal effect for the moderate class (0.638) and a negative marginal effect for the erosion-free class (−1.058), with non-significant effects for low and high classes. These coefficients should be interpreted as derivatives of predicted class probability with respect to a one-unit change in the predictor; for continuous variables such as NDVI, reporting effects for a realistic increment (for example, 0.1 NDVI units) would provide a more intuitive ecological interpretation. Slope showed smaller but significant positive marginal effects for the low (0.024) and moderate (0.047) classes and a negative effect for the erosion-free class (−0.094). Rainfall was significantly associated with the moderate class (0.011) and inversely associated with the erosion-free class (−0.017), while its effects on low and high classes were not statistically significant. NDVI had a positive marginal effect for the moderate class (0.638) and a negative marginal effect for the erosion-free class (−1.058), with non-significant effects for low and high classes. These coefficients should be interpreted as derivatives of predicted class probability with respect to a one-unit change in the predictor; for continuous variables such as NDVI, reporting effects for a realistic increment (for example, 0.1 NDVI units) would provide a more intuitive ecological interpretation.

A unit increase in sedimentary geology is associated with a 32.2% increase in the probability of a low outcome ($P = 0.004$), and increase in the probability of a moderate outcome ($P = < 0.001$). However, it is associated with decrease in the likelihood of a free class ($P = < 0.001$). The effect on the high-category class is not statistically significant. Slope also plays a role, albeit with more modest effects. It increases the probability of both low-class outcomes $P =< 0.043$) and moderate-class outcomes $P = < 0.001$), while decreasing the likelihood of a free-class outcome by ($P = < 0.000$). The effect on high outcomes is not statistically significant. Rainfall, though significant, has a limited influence, with a marginal effect on the probability of moderate outcomes ($P = < 0.014$).

The most notable effect of rainfall is a reduction in the probability of a free outcome ($P = < 0.002$), while its impact on low and high outcomes is negligible and not statistically significant. Finally, NDVI significantly influences the likelihood of moderate and free outcomes. A unit increase in NDVI increases the probability of a moderate outcome by ($P =< 0.008$) and decreases the likelihood of a free outcome by ($P =< 0.001$). Its effects on low and high outcomes are not significant.

3.4 Change in riverine gully erosion

The comparison of gully morphological characteristics between 2023 and 2025 reveals substantial and statistically significant intensification of gully erosion across all measured dimensions. The mean gully length increased significantly from 1.39 km (SD = 0.86) in 2023 to 2.22 km (SD = 1.23) in 2025 ($t = -4.87$, $P = 0.001$), indicating considerable longitudinal expansion of gullies over the study period. Similarly, mean gully depth increased from 1.62 m (SD = 0.57) to 2.26 m (SD = 0.79) ($t = -5.46$, $P =< 0.001$), while mean gully width increased from 5.95 m (SD = 2.45) to 8.12 m (SD = 2.68) ($t = -5.43$, $P = < 0.001$). These findings suggest that gullies have become significantly deeper and wider, reflecting increased erosive power and land degradation.

Significant changes were also observed in the gully area and volume. The mean gully area more than doubled from 8,856.93 m^2 (SD = 7836.70) in 2023 to 18,320.96 m^2 (SD = 13,038.60) in 2025 ($t = -4.81$, $P = < 0.001$). Likewise, the mean gully volume increased nearly threefold from 15,866.68 m^3 (SD = 16,093.31) to 47,190.00 m^3 (SD = 48,705.07) ($t = -3.92$, $P = < 0.006$). Although the relatively large standard deviations indicate substantial variability among gullies, the observed increases remain statistically significant. Generally, the results provide strong evidence that gully erosion intensified markedly between 2023 and 2025, with significant expansion in gully length, depth, width, area, and volume, highlighting the increasing severity of land degradation within the study area.

Table 5 Comparison of gully morphological characteristics between 2023 and 2025

Variable	2023		2025		t-value	*P*-value
	Mean	SD	Mean	SD		
Gully length (km)	1.39	0.86	2.22	1.23	−4.8685	0.001
Gully depth (m)	1.62	0.57	2.26	0.79	−5.46	0.001
Gully width (m)	5.95	2.45	8.12	2.68	−5.43	0.001
Area (m2)	8,856.93	7836.70	18,320.96	13,038.6	−4.81	0.001
Volume (m3)	15,866.68	16,093.31	47,190	48,705.07	−3.92	0.006

Table 6 Physical, economic and social drivers of gully erosion

Driver category	Variable	Lower n(%)	Middle n(%)	Upper n(%)	Chi-square	*P*-value
Physical	Absence of vegetation cover	13 (15.29)	5 (5.88)	67 (78.82)	13.03	< 0.001
	Concentrated runoff from steep ground	5 (6.67)	9 (12.00)	61 (81.33)	44.56	< 0.001
	Intense rainfall events	32 (37.65)	29 (14.43)	140 (69.65)	77.78	< 0.001
	Slope steepness	26 (30.59)	62 (29.67)	121 (57.89)	121.21	< 0.001
	Soil characteristics	15 (10.95)	18 (13.14)	104 (75.91)	65.31	< 0.001
	Surface water movement	5 (5.26)	11 (11.58)	79 (83.16)	61.42	< 0.001
	Weak underlying geology	4 (4.21)	10 (10.53)	81 (85.26)	64.66	< 0.001
	Total	100 (11.15)	144 (16.05)	653 (72.80)	59.99	< 0.001
Economic	Deforestation	25 (8.74)	60 (20.98)	201 (70.28)	179.55	< 0.001
	Improper land management	14 (20.00)	15 (21.43)	41 (58.57)	26.99	< 0.001
	Intensive farming	19 (9.31)	37 (18.14)	148 (72.55)	119.45	< 0.001
	Poorly constructed houses	15 (15.46)	12 (12.37)	70 (72.16)	35.5	< 0.001
	Poorly constructed roads	44 (19.13)	31 (13.48)	155 (67.39)	74.05	< 0.001
	Total	117 (13.19)	155 (17.47)	615 (69.33)	23.59	0.003
Social	Land tenure	28 (13.15)	36 (16.90)	149 (69.95)	104.21	< 0.001
	Population pressure	25 (13.09)	32 (16.75)	134 (70.16)	90.37	< 0.001
	Poverty	15 (5.81)	57 (22.09)	186 (72.09)	189.01	< 0.001
	Traditional land practices	20 (28.99)	17 (24.64)	32 (46.37)	19.51	< 0.001
	Land cover change	6 (7.89)	7 (9.21)	63 (82.89)	37.36	< 0.001
	Total	94 (11.65)	149 (18.46)	564 (69.89)	41.87	< 0.001

3.5 Perceived drivers of riverine gully erosion

The drivers of gully erosion were classified into physical, economic and social drivers (Fig. 5). The major physical drivers were slope steepness and intense rainfall, followed by soil characteristics, surface water movement, weak underlying geology, absence of vegetation cover, and concentrated runoff from the steep ground. The major economic drivers were deforestation, poorly constructed roads, and intensive farming, followed by poorly constructed houses and improper land management. Whereas the major social drivers were poverty, land tenure, and land cover change, followed by population pressure and traditional land practices (Table 5).

The drivers of riverine gully erosion were further subjected to a chi-square test to establish their association with riverine gully erosion across the different sections (upper, middle and lower) of the sub-catchment.

Physical Drivers: Table 6 shows that the absence of vegetation cover, concentrated runoff from steep ground, intense rainfall events, slope steepness, soil characteristics, surface water movement, and weak underlying geology significantly contribute to gully erosion, with all drivers having *P*-values of 0.001, indicating strong statistical significance. The most affected areas are in the upper catchment, where, for example, 78.82% show a lack of vegetation cover and 81.33% exhibit concentrated runoff from steep slopes.

Economic Drivers: Economic factors such as deforestation, improper land management, intensive farming, and poorly constructed houses and roads are significant drivers of erosion. Again, all drivers have a *P*-value of 0.001, showing a strong statistical significance (Table 6). Deforestation is particularly prominent in the upper

catchment, where 70.28% of cases are recorded. Poorly constructed roads also show a significant impact, with 67.39% occurring in the upper catchment.

Social Drivers: Land tenure, population pressure, poverty, traditional land practices, and land use/land cover change are the social drivers analysed (Table 6), all showing strong statistical significance ($P = < 0.00$). Poverty and population pressure are more prevalent in the upper catchment, with 72.09% of poverty cases and 70.16% of population pressure contributing to gully erosion. The upper and middle parts of the Lwakhakha sub-catchment consistently exhibit higher rates of riverine gully erosion across all drivers. This implies that the upper part of the catchment is most affected, attributed to steep slopes and concentrated runoff from intense rainfall.

4 Discussion

4.1 Riverine gully erosion severity distribution

The concentration of riverine gullies in the middle and upper reaches of the sub-catchment is consistent with the interaction of steep terrain, high rainfall, and intensive land use reported for Mt Elgon [33, 48]. Steeper slopes increase the gravitational component of overland flow and can enhance runoff velocity and stream power, while intense rainfall increases the likelihood that infiltration capacity is exceeded. Together, these processes favour incision, bank undercutting, and head cut retreat, particularly where vegetation or engineered drainage is inadequate [7]. The spatial clustering of gullies therefore identifies not merely locations of existing degradation but zones of strong hillslope-channel connectivity where runoff-control and bank-stabilisation measures are likely to yield the greatest benefit.

In terms of geometric characteristics, the total length of the twenty-five gullies investigated was 209,116 m. The shortest gully length was 500 m, and the longest gully length was 3860 m whereas the average gully length was 1354 m. This was much longer than studies elsewhere. For example, the longest and shortest gullies reported by Yazie et al. [74] in the Genbo Wonze watershed, Northwest Ethiopian highlands, were 1299 m and 76 m, respectively. Similarly, Alemu and Moges [1], in the Alalicha watershed, southern Ethiopia, reported that the investigated gullies had shorter lengths (427.4 m and 108 m, respectively) than those in our study area. Further still, the total surface area occupied by gullies in Lwakhakha sub-catchment was 209,116 m^2 (~10 ha), which is much bigger than the total surface area of 100,748.5 m^2 (~10 ha) occupied by twenty-two gullies in the Genbo Wonze watershed in Northwest Ethiopia. Further still, the area occupied by gullies in Lwakhakha sub-catchment is much higher than that reported by Alemu and Moges [1] in the Bora and Banda sub-watersheds in Southern Ethiopia, where gullies occupied total surface areas of 19,328.2 m^2 and 6433.2 m^2, respectively. This suggests that riverine gully erosion is reducing arable land, profoundly affecting crop production, and threatening the food security of smallholder farmers who depend entirely on land resources for their livelihoods [26, 43, 64]. These results call for immediate attention to gully erosion control and stabilisation in this sub-catchment.

In terms of gully severity, higher-severity gullies presented a higher length compared to low and moderate classes. This implies that, for the gullies under this class, the longer the gully, the higher the severity of gully erosion. The higher depth and width presented by gullies in moderate and high severity classes imply that gullies severely erode the gully bed and banks through vertical and lateral erosion, and this poses a risk to elements that are vulnerable to them, including tree roots, grazing animals, roads, and humans, both during cultivation and movement across them. In fact, wide and deep gullies are a threat to mobility between administrative units (sub-counties) (Fig. 8), which are separated by these gullies. The increase in riverine gully volume with riverine gully area in the sub-catchment was expected because most gully widths and lengths increased with an increase in gully depth. These findings imply that high-susceptibility areas are likely to experience greater gully expansion and associated loss of productive agricultural land. The results therefore provide evidence for prioritising high-susceptibility zones for gully stabilisation and for soil and water conservation interventions. Although our analysis of riverine gully distribution severity was based on field measurements, only 25 gullies were measured



Fig. 8 Gully expansion exposes woodlot roots in Bubutu sub-county, Namisindwa District

in the entire sub-catchment, which could affect the generalizability of the results especially with a much higher standard deviation. Future studies should focus on a large number of gullies to bridge this gap (Figs. 9 and 10).

4.2 Susceptibility of riverine gully erosion

Gully erosion susceptibility assessment is crucial for identifying and evaluating areas prone to gully erosion [6, 52]. It also guides land-use allocation and the prevention and control of gully erosion [72]. Random Forest model results indicate substantial spatial variability in riverine gully erosion susceptibility within the Lwakhakha sub-catchment, with the largest proportion of the sub-catchment falling within the moderate susceptibility class. This suggests that a significant portion of the sub-catchment (with moderate and high susceptibility) presents slope, elevation and NDVI characteristics that favour the initiation and development of riverine gullies. Although the moderate susceptibility class is more prevalent than the high susceptibility class, gully erosion stabilisation and control should also target areas with moderate susceptibility, as they may transition to high-susceptibility areas if runoff is not effectively controlled on steep slopes with less vegetation cover.

The best predictors of riverine gully erosion susceptibility were slope, elevation, and NDVI. This implies that, irrespective of soil type, rainfall, and geology, gully size (extent) was best determined by slope, elevation, and NDVI. The implication of these results is that areas with moderate and high susceptibility are associated with slope, elevation and NDVI characteristics that favour riverine gully development and expansion.

These results align with Amare et al. [3], who found that elevation, drainage density, land use, and groundwater were the strongest predictors of gully erosion in the Ethiopian highlands. It also conforms with people's perceptions, highlighting that steep slopes, deforestation, and road construction are the major drivers of gully erosion in the sub-catchment. However, other studies have reported other factors as best predictors of gully erosion susceptibility. For instance, Rezaei et al. [56] reported that land use, land cover, lithology, and distance to



Fig. 9 One of the roads in Bumwoni sub-county destroyed by gully erosion, Namisindwa District

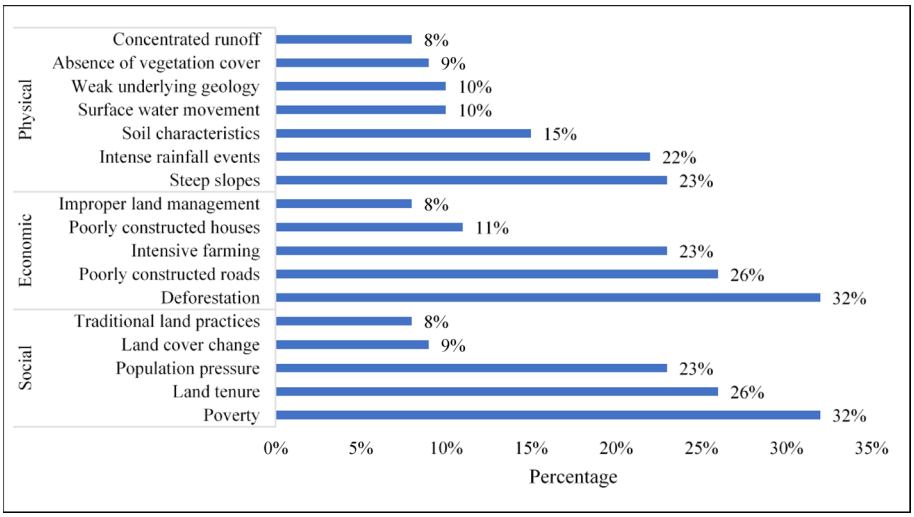


Fig. 10 Drivers of riverine gully erosion in Lwakhakha sub-catchment

roads mostly affect the occurrence of gully erosion in the Toroud watershed, Semnan province, Iran. In another study, Arabameri et al. [5] report distance to the road, land use, land cover, and distance to a stream as the best predictors of gully erosion. These findings demonstrate the usefulness of the Random Forest model in identifying gully erosion hotspots. This helps to distinguish areas with different levels of erosion risk and therefore supports spatially targeted soil and water conservation planning. Our study contributed to a gully erosion susceptibility map, which is critical in guiding environmental policymaking and sub-catchment management efforts. Critically, high-susceptibility zones should be targeted for intensive gully stabilization, while moderate-susceptibility areas should receive preventive conservation measures.

4.3 Relationship between major gully drivers and gully erosion classes

The multinomial model results demonstrate that sedimentary geology and NDVI are the most substantial determinants of gully erosion in the Lwakhakha sub-catchment. Sedimentary geology, for example, has a positive and significant influence on the low and moderate classes. This implies that areas dominated by sedimentary rock formations are highly susceptible to low- and moderate-erosion classes. Such formations are often weakly consolidated and easily detached by runoff, thereby encouraging gully initiation and expansion [46]. The absence of a statistically significant relationship with the high erosion class implies that although sedimentary geology promotes the occurrence of gullies, it does not necessarily determine the transition to the most severe erosion category [51]. Similarly, a unit increase in NDVI strongly increases the likelihood of the moderate erosion class and decreases the probability of the free class. Since NDVI typically represents vegetation density, which is generally expected to reduce erosion risk. The positive association between NDVI and moderate erosion suggests that NDVI may capture seasonal vegetation responses rather than long-term protective cover [57]. In other cases, the presence of vegetation may correspond to humid zones that also experience higher runoff, steep slopes, and land-use patterns where vegetation regrowth occurs after erosion has already developed [67, 68]. The influence of NDVI on low and high erosion classes was insignificant. These results are expected because high vegetation density limits the effects of rainfall-induced soil detachment and slows runoff, thereby reducing rainwater's erosive power. Implying that runoff volumes and sediment load of bare plots are greater than those of vegetation-covered plots [79].

Slope also considerably increases the likelihood of low and moderate erosion classes while reducing the likelihood of being erosion-free. Nevertheless, steep slopes increase runoff which increases susceptibility to erosivity and slope erodibility, thereby increasing soil detachment and channel incision and widening [44]. However, the relatively small marginal effects indicate that slope alone is not a dominant driver but works in combination with other factors. The non-significant effect in the high-erosion class further suggests that steepness may facilitate the initiation of erosion but does not independently account for the development of severe gullies [73]. These results show that although rainfall influences gully erosion, its effect is weakly related to the moderate and free classes. However, its effect on the lower and upper classes is not statistically significant. This implies that rainfall enhances runoff generation and soil erosion; its independent contribution is limited. This is true because rainfall works hand in hand with other factors such as slope, geology, drainage characteristics, and vegetation cover. Rainfall acts more as a triggering factor than a sole determinant of gully severity [35]. Generally, these results suggest that severe erosion requires a combined influence of environmental factors (slope, geology, rainfall intensity, and poor vegetation cover) and anthropogenic factors (land use and land cover, road construction, deforestation, etc.). This implies that riverine gully erosion interventions in Lwakhakha should focus on both environmental and anthropogenic factors.

4.4 Change in riverine gully erosion

Riverine gullies showed a statistically significant increase in all morphological characteristics between 2023 and 2025. Although expected, the increase was much higher within the three years. Our results indicate that gullies in the study area became longer, deeper, wider, larger in surface area, and greater in volume over the three-year period. This implies that gullies are actively increasing, partly due to the cultivation of annual crops on steep slopes without proper soil and water management practices. Annual crops like maize and sorghum require intensive and continuous tillage from planting to harvesting, which weakens the soil and generates a deep, compacted layer that reduces infiltration and accelerates runoff into already-developed gullies [11].

The gully area showed the most distinct change among the morphological characteristics. The change in gully area implies that the average area affected by riverine gullies more than doubled, which is far higher than what Yibeltal et al. [76] found in the Pairs Guder, Aba Gerima, and Dibatie watersheds in Ethiopia. Our results, however, differ from those reported by Litvin and Kiryukhina [37] and Yermolaev et al. [75] in the European part of

Russia, where gully length was reduced due to changes in land-use patterns. High rainfall magnitudes trigger and accelerate gully head-cut retreat rates, thereby increasing gully length [34, 59]. This confirms what Shruthi et al. [61] found in the Sehoul sub-humid to semi-arid region of Morocco, where high rainfall, steep slopes, tillage, and crop management practices were the major drivers of changes in gully erosion.

Concentrated runoff from roads also rapidly widens and deepens gully channels downstream, especially where culverts release water into unprotected slopes [23, 52]. In the study area, culverts along the Lwakhakha main road release large volumes of water that flow into downstream gully erosion channels, thereby deepening and widening them. In the Gumara watershed, Northwestern Ethiopia, a temporal trend analysis of gully erosion change showed an average short-term change in gully length of 13.44 m ha per year and a medium-term average rate of increase in length of 0.668 m ha per year [9]. These results indicate that gullies increase in number during the initial stages of development, and that the rate of development decreases over time.

In this study, riverine gully change was assessed over only two years, which may have negatively influenced the results; we recommend further studies that conduct a spatio-temporal analysis of gully erosion change in the sub-catchment over a longer period. This would also help assess changes in gully density and ascertain the rate of gully expansion in the sub-catchment. Nevertheless, our results provide strong evidence that gully erosion is increasing in both area and volume, indicating substantial expansion in the spatial extent and magnitude of soil loss, as our study was based on field measurements. These findings highlight the need for urgent, holistic gully stabilization and catchment-level soil and water conservation interventions to prevent the expansion of existing gullies and the initiation of new ones in the intervention area.

4.5 Perceived drivers of riverine gully erosion

The upper and middle parts of the Lwakhakha sub-catchment consistently exhibit higher rates of riverine gully erosion across all drivers. This implies that these sections of the sub-catchment are the most affected, attributed to steep slopes and concentrated runoff from intense rainfall [33]. Intense rainfall, for instance, increases erosivity on these steep slopes, leading to the development of gullies [66]. Additionally, high rainfall magnitudes trigger and accelerate gully head cut retreat rates. Similar results are reported by Habtu and Jayappa [27] in a study conducted in the Megech-Dirma watershed in Northwest Ethiopia. Whereas previous studies [7, 33, 50] on the Mt. Elgon catchment attribute soil erosion primarily to physical factors, this study found road construction, land tenure, population pressure, and poverty to be among the major causes of riverine gully erosion. The construction of the highway to the Lwakhakha border intensified gully erosion in the study area by increasing concentrated runoff from the culverts. Concentrated runoff from roads rapidly causes gully development and downstream widening of gully channels, especially where culverts release large volumes of water onto unprotected slopes [23, 52]. Road construction also increases gully head retreat [49] and the gully drainage area [22], which leads to the loss of fertile soils, reduces arable land, impedes tillage operations, and eventually affects crop productivity [49]. The effects of road construction on gully erosion have also been reported elsewhere. For example, Yazie et al. [74] reported it as the major cause of gully erosion in the Gendo Wonze watershed in the northwestern Ethiopian Highlands. In Chepareria, West Pokot County, Kenya, Churu et al. [16] reported deforestation and surface runoff as major causes of gully erosion, which conforms to this study's findings. The Lwakhakha sub-catchment is dominated by smallholder farmers whose farming is subsistence-based, relying mostly on the limited available land. This has forced them to encroach on marginal lands such as mountain slopes, causing deforestation and further exacerbating gully erosion.

5 Conclusion

This study's findings demonstrate that riverine gully erosion exhibits greater morphological development in the middle and upper catchment. The positive relationship between gully area and volume indicates that expansion of gully extent is accompanied by increased soil loss and erosional intensity. These areas therefore constitute critical hotspots of land degradation and should be prioritised for targeted stabilisation and catchment management interventions. The Multinomial and RF models provide empirical evidence on gully erosion hotspots in river catchments. This therefore provides important information on the priority areas where to direct the limited resources for gully erosion stabilization and control, especially in resource-scarce economies. These models also provide site-specific best predictors of gully erosion, which help identify which environmental factors to consider when designing gully erosion stabilization technologies and soil and water conservation practices.

Erosional gullies in the sub-catchment are actively increasing, with most of the increase observed in gully area and volume. This has a profound effect on agricultural land, soil loss and fertility, which generally reduces agricultural productivity. These findings highlight the need for urgent, holistic gully stabilization and catchment-level soil and water conservation interventions to prevent the expansion of existing gullies and the initiation of new ones. Our results also highlight the importance of using GIS and Remote Sensing in gully-affected areas for regular monitoring of already existing gullies and identifying newly developing gullies in order to guide gully erosion control projects. Our findings suggest that riverine gully erosion intervention efforts should concentrate in the upper and middle sub-sections of the sub-catchment with focus on mitigating physical factors (such as runoff management and vegetation restoration), economic factors (such as deforestation and infrastructure development), and social drivers (such as poverty alleviation and improved land tenure systems). Although drivers of gully erosion are site-specific, intervention measures in tropical catchments should address both environmental and human factors.

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Author contributions CN conceptualized the study problem and design, collected the data, analysed and interpreted it, prepared all the figures, and substantially participated in drafting the manuscript. BB conceptualized the study design, substantially contributed to the drafting of the article, made reviews and approved the submitted version of the manuscript. CW reviewed the drafts and approved the submitted version of the manuscript. AM participated in data collection and data analysis.

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Data availability The datasets used and analyzed in this study are available from the corresponding author on reasonable request.

Declarations

Competing interests 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.

Ethics approval and consent to participate This study was approved by the Uganda Christian University Research Ethics Committee (UCU-REC), (UCUREC-2025-1930), and all methods performed were in accordance with the guidelines and regulations of the UCU-REC. In addition, informed consent was obtained from all participants in this study. Informed consent was obtained from individual participants that we contacted in this study.

Consent for publication Not applicable.

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