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Research Article

Evolution of gully erosion and susceptibility factors in the urban watershed of the Kimemi (Butembo/DR Congo)

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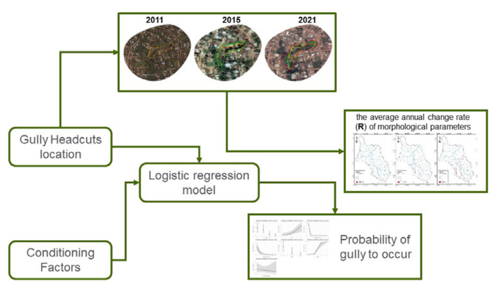
HIGHLIGHTS

- Gully erosion dynamic was assessed using Google Earth images and field data.
- The area of land degraded by gully erosion has been increased by four times over a decade.
- A combination of physical and anthropogenic factors makes land vulnerable to gully erosion.

GRAPHICAL ABSTRACT



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ABSTRACT

Gully erosion is one of the most intense landscape degradation mechanisms in areas with varying environmental characteristics. Both natural and anthropogenic factors affect the gullying process. Reliable documentation of these processes in tropical African cities is scarce. This study assessed the gully erosion dynamic and the susceptibility factors in the urban watershed of Kimemi in eastern Democratic Republic of Congo (DRC). Data were obtained through a combination of fieldwork and digitization of very high spatial resolution images from Google Earth (from 2011 to 2021). The length, width, and area of large gullies (width $\geq$ 5 m) were measured for each year of the study. A logistic regression model (LRM) was also used to investigate the influence of both physical and anthropogenic factors on gully susceptibility. The results revealed that the number of gullies has increased from 36 to 61 during the last decade. The gully mean length of 63.9 $\pm$ 61.1 m, 129.3 $\pm$ 104.9 m, and 174.7 $\pm$ 153.8 m were obtained for the years 2011, 2015, and 2021 respectively. The average density of gully network for the study period was 0.12 km/km^2, while the degraded land was ~1.3 and ~1.1 ha/year for 2011–2015 and 2015–2021 for the entire watershed. The significant changes in morphometric parameters (length, width, area) were found only in the bare land and building land uses. A strong and positive relationship between the length (m) and the area (ha) was found. Furthermore, the susceptibility of gullying was significantly influenced by the slope, stream power index (SPI), distance to roads and rivers, land use and land cover (LULC), and normalized difference vegetation index (NDVI). This means the areas located in the bare land and building or close to roads and/or streams are more likely to be gullied. The findings emphasize the impact of urbanization on gully erosion in the Kimemi watershed, highlighting the importance of informed land management decisions with a close attention to anthropogenic factors.

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1. Introduction

Gully erosion is one of the most intense and difficult landscape degradation mechanisms to control (Zabihi et al., 2018; Sow, 2020). It extends to several areas under various climatic conditions (Menéndez-Duarte et al., 2007) and occurs in various land uses with a high frequency in man-made areas such as cities and towns. Many urban areas throughout the tropical region are confronted with gully erosion problems (Ilombe et al., 2021; Zolezzi et al., 2018). The urbanization process as human pressure combined with environmental perturbations contributes to the amplification of the gullying process (De Geeter et al., 2023). High damage from settlement structures, modifications of the hydrology of the catchment, and the increases in sediment deposition on downstream are the main sources of gully erosion (Valentin et al., 2005; Busnelli et al., 2006; Junior et al., 2010; Kayembe and Wolff, 2015; Lopanza et al., 2020). Nevertheless, the gully erosion process seems to result from the encounter between natural events and anthropogenic factors (Junior et al., 2010; Rahmati et al., 2022). Moreover, the urbanization process is still progressing in several cities in developing countries and generates several environmental issues (Angel et al., 2011; Tumwesigye et al., 2021). In the meanwhile, urbanization in tropical regions generally takes place in an uncontrolled manner with an increase in impervious surfaces (Karolien et al., 2012; Sikuzani et al., 2018); it highly contributes to runoff increase in the watershed (Adediji et al., 2013; Rodrigues et al., 2022).

Similarly to other developing countries, the uncontrolled urbanization is occurring in Democratic Republic of Congo (DRC). This uncontrolled urbanization contributes to the increase in environmental problems and studies indicate that gully erosion and landslides are among the main ones in DRC (Sahani et al., 2014; Bayumbasire et al., 2021; Mutungu et al., 2021; Lutete et al., 2023). Unfortunately, evidence from Ilombe et al. (2021) mentioned that the impacts of gully phenomena in these cities and urban centers are constantly increasing. Although Butembo city did not present a major risk of gullying more than half a century ago, it is now becoming more and more a veritable environmental challenge (Sahani, 2011). This phenomenon is one of the obstacles to sustainable development in the region (Moeyersons et al., 2015). In fact, the evolution of the gully in this city leads to the loss of plots of land, the destruction of houses and bridges, roads, etc. Preventive measures to curb this risk require understanding the dynamic of the phenomenon and the knowledge of the effects of each controlling factor (Valentin et al., 2005; Vanmaercke et al., 2021). For example, slope and drainage areas (Makanzu Imwangana et al., 2014) have a significant influence on gully head initiation during heavy rainfall (Anderson et al., 2021). In addition, roads (Seutloali et al., 2016; Gudino-Elizondo et al., 2018) and changes in land use characterized by the reduction of vegetation (Chuma et al., 2021; Mokarram and Zarei, 2021) amplify gully erosion process.

Studies of gully erosion available in Butembo are limited and moslty focused on isolated cases that do not take into account the watershed management approach (Sahani, 2011; Mukandala and Menomavuya, 2021). However, according to Sow (2020), the watershed is an integrating territory for hydrological processes that evolve in time and space under the influence of humans. Poesen (2018) and Cotler and Ortega-Larrocea (2006) state that the spatial scale is an important element in understanding soil water erosion.

Characterization, dynamics, and factors leading to gully expansion in tropical region are still limited; only few case studies are documented. As a consequence, decision-makers rely on case studies from arid or semi-arid regions that have completely different conditions to local ones. Thus, efficiency and decision orientation are limited (or not applicable). The case of eastern DRC urban watershed such as the Kimemi in Butembo is among others; less documentation lead to weak interventions, and the efforts to mitigate the effects remain limited. Obtaining such information is limited in terms of time and material consuming (Chuma et al., 2021). Very high spatial, temporal, and spectral resolution images combined with ground truth data allow for easier research and help to understand how this process changes across time and space. Therefore, they are essential components of gullying monitoring and evaluation. However, obtaining these expensive and challenging to handle data continues to be one of the major constraints. Additionally, it is challenging to process these data into a temporal series (McInnes et al., 2011). To study these areas or those types of phenomena that seem more dynamic in space and time, fast-access image data (like Google Earth) are useful; they have to be followed by field observations and validation (Vrieling, 2006; Boardman, 2016; Chuma et al., 2021).

Therefore, this study contributes to fill the gap of anthropogenic pressure on land by evaluating the gully erosion rate and factors affecting gully susceptibility in an urban watershed located in the equatorial zone, since watershed is considered as a basic scale for development planning (Rodrigues et al., 2022). In this study, it is assumed that using Google Earth images would make it possible to track the gully process occurring at the watershed scale, and the changes in the gully evolution and susceptibility.

The objectives of this study are to (i) quantify changes in gully morphometric parameters accross different land use classes from 2011 to 2021, (ii) evaluate the factors affecting the gully susceptibility in the Kimemi watershed.

2. Materials and methods

2.1. Study area

The Kimemi watershed is located in Butembo City, North-Kivu Province, east of DR Congo. It lies at 0°05′N–0°12.5′N and 29°15′E–29°20′E (Fig. 1). This watershed is named after the main river, Kimemi, which drains its water from south to north. The Wayimirya, Kanywangoko, Kavaghendi, and Kinyavuyiri are the most known and important streams in the watershed (Mahamba et al., 2022). The watershed is located between 1,676 m and 2,016 m above sea level (a.s.l). The average slope in the catchment is ~10.6°. Based on the morphological and hydrological characteristics, the area is ~64.5 km^2 (and the perimeter is 46.1 km) leading to a Gravelius compactness index of 1.6. The average drainage density (Dd) is ~1.88 km/km^2. Fig. 1 shows the location of the Kimemi watershed.

The Kimemi watershed lies on a geological foundation made by three main rock types. From northwest to the southeast, these are: (i) Luhule-Mobisio Basic Complex (of metabasalts, dolerites, diorites, and quartzite islands), (ii) Luhule-Mobisio Sedimentary Bedrock (composed of schists, quartzites with limestone intercalations), (iii) Orthogeneissic Complex (Fig. 2 (a)). The soil types depend on the underlying geological substratum. Thus, two types of soils predominate in the Kimemi catchment. The first type consists of Hygro-Xero-Kaolisols and the second is made up of humus-bearing Hygro-Kaolisols with humus with a dark horizon (Fig. 2(b)). These different soil types are modified by the local conditions (Sahani, 2011).

The Kimemi watershed is located in a typical equatorial region, in which the climate is contrasted by mountains. According to available data, the annual mean temperature and rainfall fluctuate around ~18 °C and ~1,400 mm, respectively (Vyakuno, 2006; Sahani, 2011). The watershed is densely (~8,856 people/km^2) populated and represents approximately 61% of Butembo's population by referring to the city hall archives of 2020. In the local culture of the population, the land is a part of their identity and serves as a place to live, but also for economic activities (Kitakya, 2007). The population living in the Kimemi watershed in particular and in the city of Butembo, practice trade and agriculture as their main economic activity (Mafikiri Tsongo, 2021).

From the mid-20th century to the present day, this watershed has experienced increasing urbanization, resulting in the expansion of bare land and building at the expense of woodlands and other vegetated areas (Fig. 3) (Sahani, 2011; Mahamba et al., 2022). The houses are built

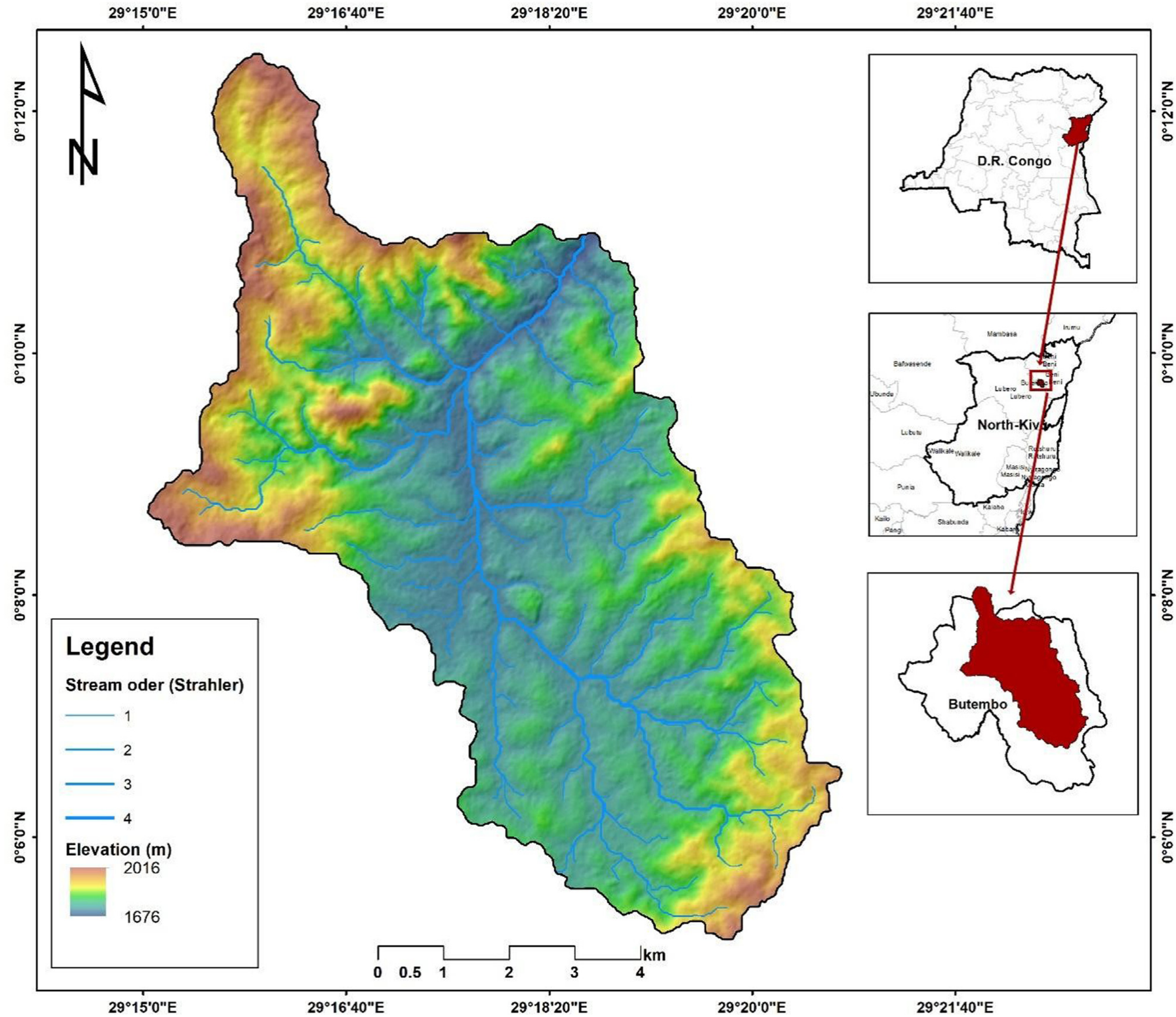

Fig. 1. Location of the Kimemi watershed in the Butembo City, province of North-Kivu, eastern DRC. Numbers represent the stream order extracted from ArcGIS 10.3 according to the Strahler method.

on hillsides in some places and the roads, especially several access pathways, are built generally in the direction of the slope.

The original vegetation of the Kimemi watershed has already been removed, and hence opening a way to exotic stands of *Eucalyptus* sp., *Leucaena leucocephala, Calliandra calothyrsus, Albizia* sp., *Erythrina* sp., and *Grevillea robusta* species. A few herbaceous species are visible in empty plots and urban fields. Fig. 3 shows the land use in 2011, 2015, and 2021.

2.2. Data collection

Several fieldwork visits were organized from July to September 2021 to make an inventory of gullies within the Kememi watershed. During the fieldwork, the gully headcuts were georeferenced, and pictures were taken to illustrate the phenomenon. This inventory was followed and completed by visual interpretation of Google Earth images. A total of 155 gully headcuts were identified when combining the field expedition and the visual interpretation of Google Earth images.

The years 2011, 2015, and 2021 were chosen mainly based on the availability of images and the classified Landsat images matching for land use and land cover. Data on morphometric parameters, i.e., length (L), top width (w) and area (A), of gullies were obtained by digitization on Google Earth images. These very high-resolution (±0.6 m) images available on *Google Earth Pro* allowed us to investigate on geographical features with good planimetric and altimetric accuracy (Frankl et al., 2013a).

The LULC data were based on the results from Mahamba et al. (2022). They were obtained following the supervised classification of Landsat images with 30 m of spatial resolution. These images were from the ETM+ sensors (Enhanced Thematic Mapper) for the year 2011 and OLI/TIRS (Operational Land Imager/Thermal Infrared Sensor) for 2015 and 2021. The classes that have been retained include bare land and building/settlements (houses, roads, and bare fields lands), grasslands (combining grass and cultivated lands, etc.), and woodlands (shrubbery and forest plantations).

The digital elevation model (DEM) of 2010 with a spatial resolution of 12.5 m was used to assess the topographic and hydrological factors; it was also used to delineate the watershed. The DEM was derived from the ALOS PALSAR satellite. It was available on the Earthdata website (https://search.asf.alaska.edu/#/). In addition, the road layer that was used to calculate the Euclidean distances was taken from the *Open Street* database, via the *BBBIKE* platform (https://extract.bbbike.org).

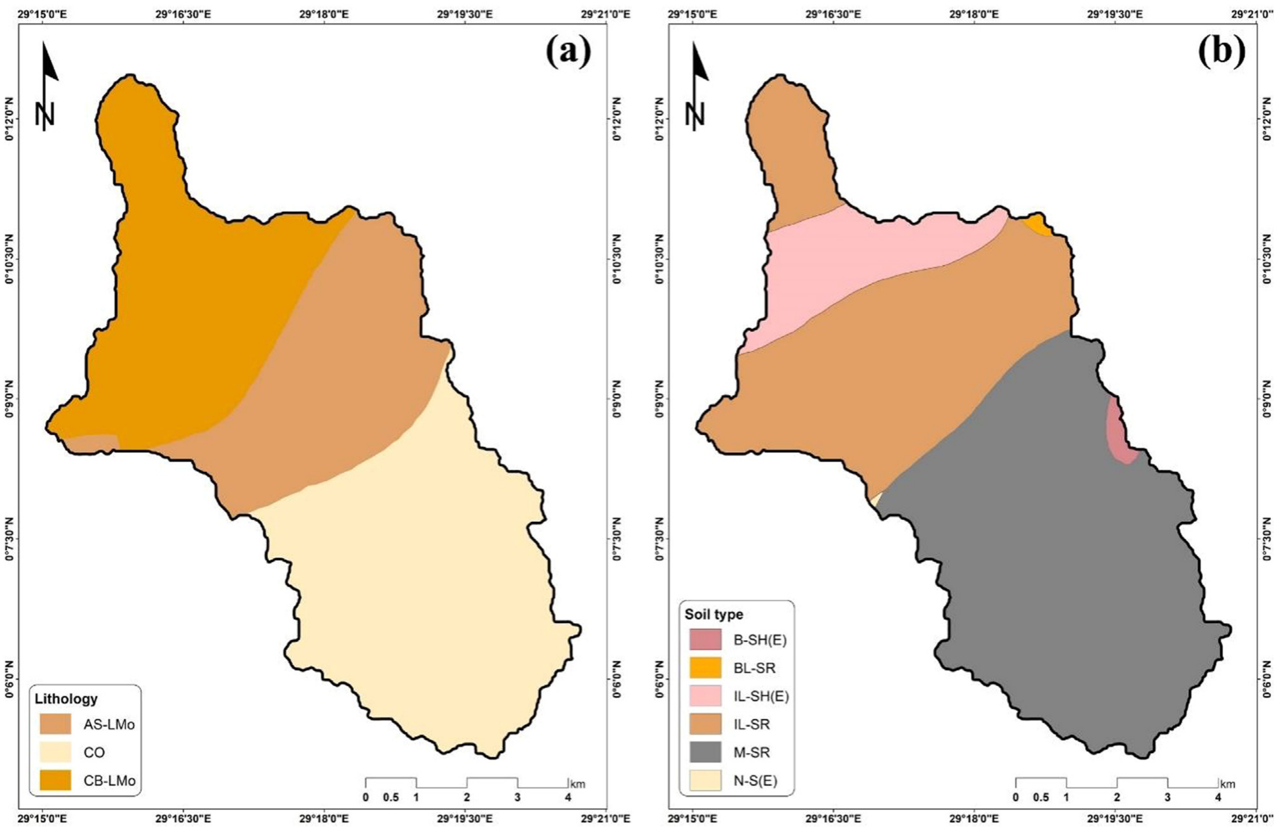

Fig. 2. (a) Rock types (AS-LMo, Luhule Mombisio sedimentary bedrock; CO, Ortho-Gneissic Complex; CB-LMo, Luhule Mombisio Basic Complex) and (b) soil types in the Kimemi watershed (B-SH(E), Humiferous Hygro-Kaolisols on bedrock; BL-SR, Humiferous Hygro-Kaolisols with dark horizon on bedrock in relation to the leveling surface; IL-SH(E), Humiferous Hygro-Kaolisols on shale and bedrock phyllado in relation to the leveling surface; IL-SR, Humiferous Hygro-Kaolisols with dark horizon on shale and phyllodes basic rock in relation to the leveling surface; M-SR, Humiferous Hygro-Kaolisols with dark horizon on micaceous rocks; N-S(E), Hygro-xero-kaolisols on granito-gneiss). Map data *source*: Royal Museum of Tervuren.

2.3. Methods

2.3.1. Changes in the morphological parameters of gullies

The gully density (expressed in km/km^2) was assessed for each study year. In addition, the top widths, lengths, and areas of large gullies obtained for the years 2011, 2015, and 2021 were subjected to the calculation of the average annual change rate (R) to quantify the change over time. The R was calculated according to Eq. (1) (Vandeschrick, 2021):

$$\boldsymbol{R} = \left(\sqrt[n]{\frac{\boldsymbol{x_f}}{\boldsymbol{x_i}}} - 1 \right) \times 100 \tag{1}$$

where:

R refers to the average annual change rate; x_f refers to the value of the parameter at the final time; x_i refers to the value of the parameter at the initial time; and n is the number of years elapsed during the period studied.

The significance of changes in morphological parameters (length, top width, and area) occurring in respective LULC classes was performed using the Kruskal-Wallis rank test at the α=5% threshold. This was done since the data of length, width, and area of gullies do not respect the condition of normality and homogeneity of variance. Kruskal-Wallis is a nonparametric test based on the calculation of the ranks (McKight and Najab, 2010). The data visualization by boxplots with p-values indicating the level of significance was carried out using the packages "*ggplot2"* (Wickham, 2016) and "*ggpubr*" (Kassambara, 2020) in R 4.1.2 and RStudio (R Core Team, 2021). Finally, the Spearman correlation coefficient and simple linear regression were performed to evaluate the relationship between morphometric variables in the LULC classes. The correlation matrix was obtained using the "*GGally*"package (Schloerke et al., 2018) and the representation of the regression trend lines with its parameters (regression equation, coefficient of determination: R^2-Adjusted) was performed using the functions of the "*ggplot2"* package.

2.3.2. Effect of selected factors on gully susceptibility

A wide range of factors (Valentin et al., 2005; Vanmaercke et al., 2021; Rahmati et al., 2022) influences the gullying phenomenon. These factors are not known in advance, and the choice of these factors for this study was based on the data availability, the physical environment, and the interactions between these factors (Gayen et al., 2019; Razavi-termeh et al., 2020). Initially, several (14) factors were selected for this study based on experts' statements, literature, and previous research conducted in various areas (Hembram et al., 2020; Rahmati et al., 2022; Valentin et al., 2005). These factors are topographic, hydrological, geological, pedological, climatic, and anthropogenic. In summary, 14 factors were initially considered for this study comprising: (i) elevation (m), (ii) slope (°), (iii) plane curvature (100/m), (iv) slope length factor (LS), (v) topographic wetness index (TWI), (vi) stream power index (SPI), (vii) drainage density, (viii) distance to river (m), (ix) distance to road (m), (x) annual mean precipitation (mm), (xi) soil types, (xii) lithology, (xiii) land use and land cover (LULC) classes, and (xiv) normalized difference vegetation index (NDVI).

Six topographic variables (elevation, slope, plan curvature, slope length, TWI, SPI) and two hydrological (river distance, drainage density) factors were obtained using the ALOS PALSAR DEM; while LULC and NDVI were derived from the Landsat image of 2021 (Section 2.2). Spatial distributions of rock and soil types were obtained by geo-referencing the geological and soil maps from the Royal Museum of Tervuren. Finally, the Euclidean distance to roads was also calculated using the road

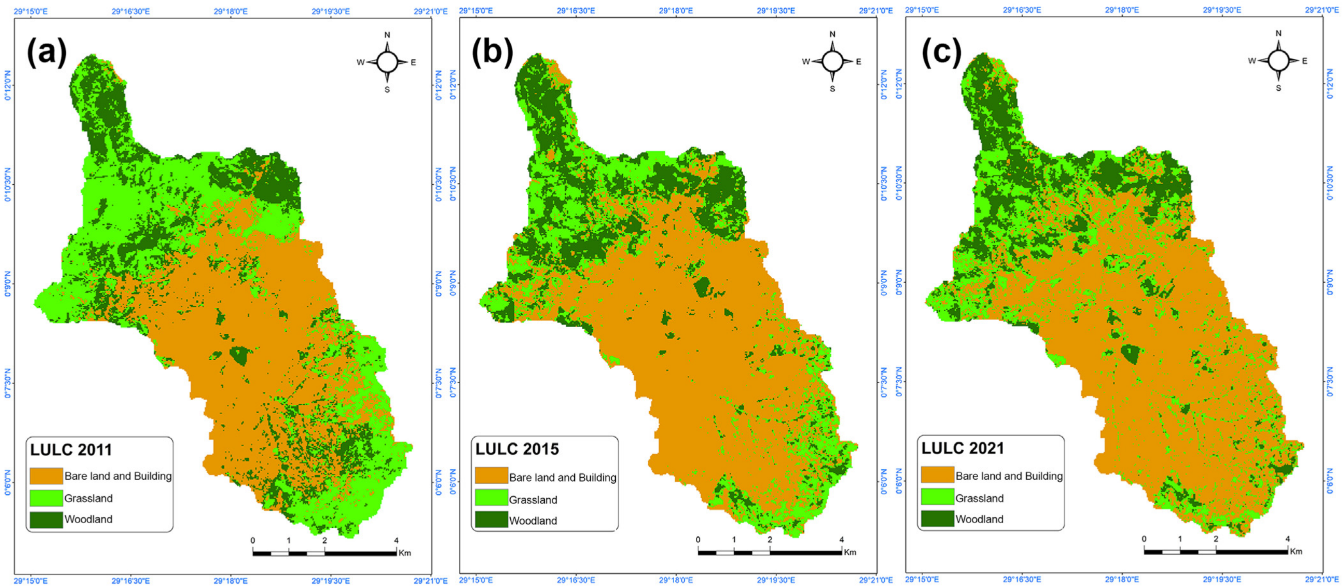

Fig. 3. Land use and land cover in (a) 2011, (b) 2015 and (c) 2021. Adapted from Mahamba et al. (2022).

layer extracted from the open street database via spatial analysis tools from ArcGIS 10.3. For each gully headcut (155) identified in 2021, we have associated the values of all the considered factors. All these operations were carried out with ArcGIS10.3 Esri-TM software. A detailed explanation of factors is presented in the supplementary material (Table S1).

To assess the effect of selected factors on gully susceptibility, a logistic regression model (LRM) was used. This model was chosen because it is relatively simple to implement and allows integration of both qualitative and quantitative variables to explain the variable of interest (Conoscenti et al., 2014). According to Arabameri et al. (2021) the selection of a model depends on the nature of the variable to be explained, the objectives and the availability of data as well as the time and simplicity of the model. Binary logistic regression is a special case of simple linear regression in which the dependent variable is binary (Conoscenti et al., 2014). In this case, the dependent variable is the occurrence of gully (gully/no gully). The logistic regression model calculates the probability (*P*) of an event occurring according to Eq. (2) (Sheather, 2009):

$$P(Y = 1) = \frac{1}{1 + e^{-\beta_i X_i}} \tag{2}$$

where *P* is the probability of the presence of gully headcuts; $\beta_i X_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_p X_p$, β_0 is the intercept, β_i represents the regression coefficient of each independent variable X_i (i = 1, ..., p). Coefficients β_0 and β_i were estimated using generalized linear model (GLM) with the Logit function according to a maximum likelihood approach (Tuffery, 2017). Using this model, the marginal probability $P(Y = 1/X{=}X_i)$ of the dependent variable (e.g., presence of gullying) is estimated given the observed values of the independent variable X_i (Sheather, 2009; Dinov, 2018).

The GLM procedure of the *MASS* package (Ripley et al., 2013) was followed to perform the logistic regression in R software (R Core Team, 2021). The explanatory variables with significance at the 5% level were identified by analysis of the variance of the previously created logistic model. The accuracy of the applied model was tested using AIC (Akaike information criterion). A stepwise backward selection was applied to the initial model (containing all factors) in order to retain a group of factors that have a more significant effect on the gully susceptibility. The *stepAIC* function of the "*MASS*" package in R software was used (R Core Team, 2021). This function aims to identify the factors that minimize the AIC of the model. Therefore, six factors have been retained: slope angle at the gully headcut, SPI, Euclidean distance to roads, Euclidean distance to streams, LULC, and NDVI. The results for the full model are presented in supplementary material (Table S2). The marginal probability of gully occurrence for all factors of the selected model was represented graphically using the package "*ggeffects"* of R software (Lüdecke, 2018).

3. Results

3.1. Dynamics of the gully network morphology

3.1.1. Length, top width, area and gully density

Field observations and digitization of Google Earth images allowed the mapping of a set of 30, 53, and 60 gullies for the years 2011, 2015 and 2021 respectively, with at least 5 m of top width. The evolution of gully morphology is marked by high average annual change rates (*R*) between 2011 and 2015, which significantly decreased between 2015 and 2021 (Table 1). Between 2011 and 2015, the total length of gullies increased at an average annual rate of 24.2%. However, this rate decreased to 6.4% between 2015 and 2021 (Table 1). Similarly, the average annual growth in the total area was 28.0% between 2011 and 2015 before being reduced to 9.2% in the period 2015–2021 (Table 1).

In a decade period (2011–2021), the total gullied area in the Kimemi watershed has increased by a factor of 4 from 46,964.7 m^2 to 214,332 m^2. This is equivalent to 13,150.1 m^2/year of degraded land from 2011 to 2015 and 11,610.7 m^2/year from 2015 to 2021. The distribution of the gully areas showed wide range, with values ranging from 84.5 m^2 to 68,318.4 m^2 for the year 2021.

The average gully lengths were 61.1 ± 63.9 m, 129.3 ± 104.9 m, and 174.7 ± 153.8 m respectively for the years 2011, 2015, and 2021.

Table 1
Temporal variations of the morphological characteristics of gullies. *L*, Total length; *A*, Total area; *D*, Density; *N*, Number of gullies.

Parameter	2011	2015	2021	*R* in%	
				2011–2015	2015–2021
L (m)	3,592.6	8,541.8	12,368.2	24.2	6.4
A (m^2)	46,964.7	126,203	214,332.8	28.0	9.2
D (km/km^2)	0.06	0.1	0.2	–	–
N	36	54	61	10.7	2.1

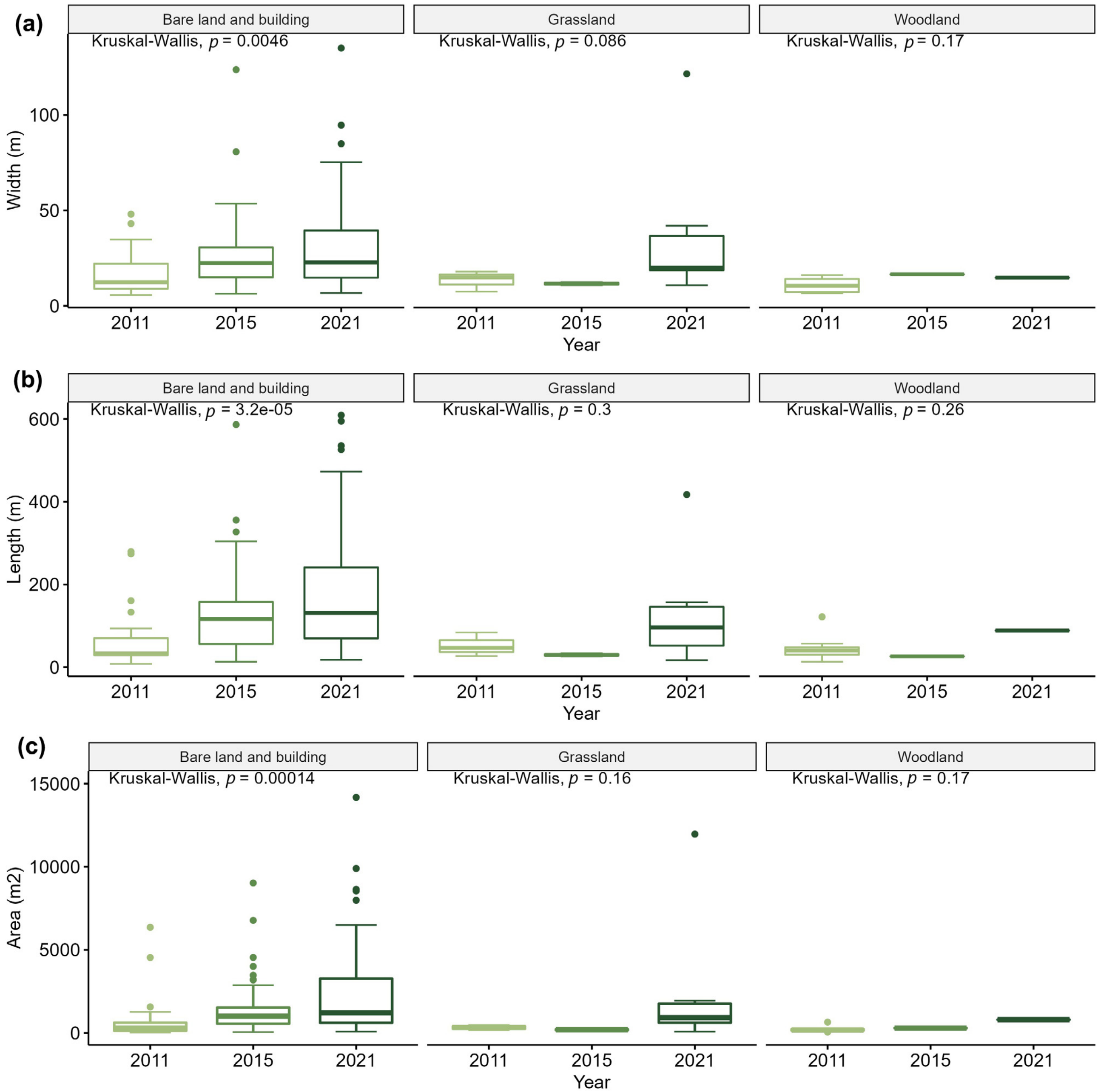

Fig. 4. Distribution of width (a), length (b) and area (c) of the gullies. Values were separated from one land use and land cover to another; the period from 2011 to 2021 was selected. The nonparametric Kruskal-Wallis test was performed at 5% probability threshold (p>0.05, non significant (ns); p<0.05, significant (**); p<0.01, highly significant (***)).

Density also increased from 0.06 km/km^2 to 0.13 km/km^2 between 2011 and 2015, before reaching 0.19 km/km^2 in 2021 (Table 1). The average density during the study decade was 0.12 km/km^2. Furthermore, the average top width of the gully increased from 15.6 ± 10.4 m in 2011 to 26.4 ± 19.9 m in 2015, and to 32.8 ± 27.1 m in 2021.

The Kruskal-Wallis test revealed that all changes in the morphological parameters of the gully network were significant only in the bare land and building class ($p < 0.05$) (Fig. 4) and the distributions of area, length and width values were significantly ($p < 0.05$) different between LULC classes in 2015 only. It should be noted that the averages for all morphological parameters were calculated without considering the largest gully in the Wayimirya tributary valley (Fig. 5(b)). In fact, the values of the morphological parameters of this large Wayimirya gully deviated widely from the overall distribution of the watershed gully network (in 2021, area: 68,318.4 m^2, length: 1,885.6 m, width: 365.4 m). This gully alone covered 31.9% of the total gully area. Gully erosion was widening and caused a lot of damage to the infrastructure (residential houses and roads) (Fig. 6).

3.1.2. *Relationship between gully morphological parameters*

The results revealed that all the selected parameters were significantly and positively correlated to each other (Fig. 7). On one hand, the Spearman correlation coefficients of 0.825 and 0.897 were obtained between the area and the top width, and the area and the length, respectively. Finally, the Spearman correlation coefficient of 0.781 was obtained between gully length and top width. On the other hand, gully length explains better the variations of gully area than the top width

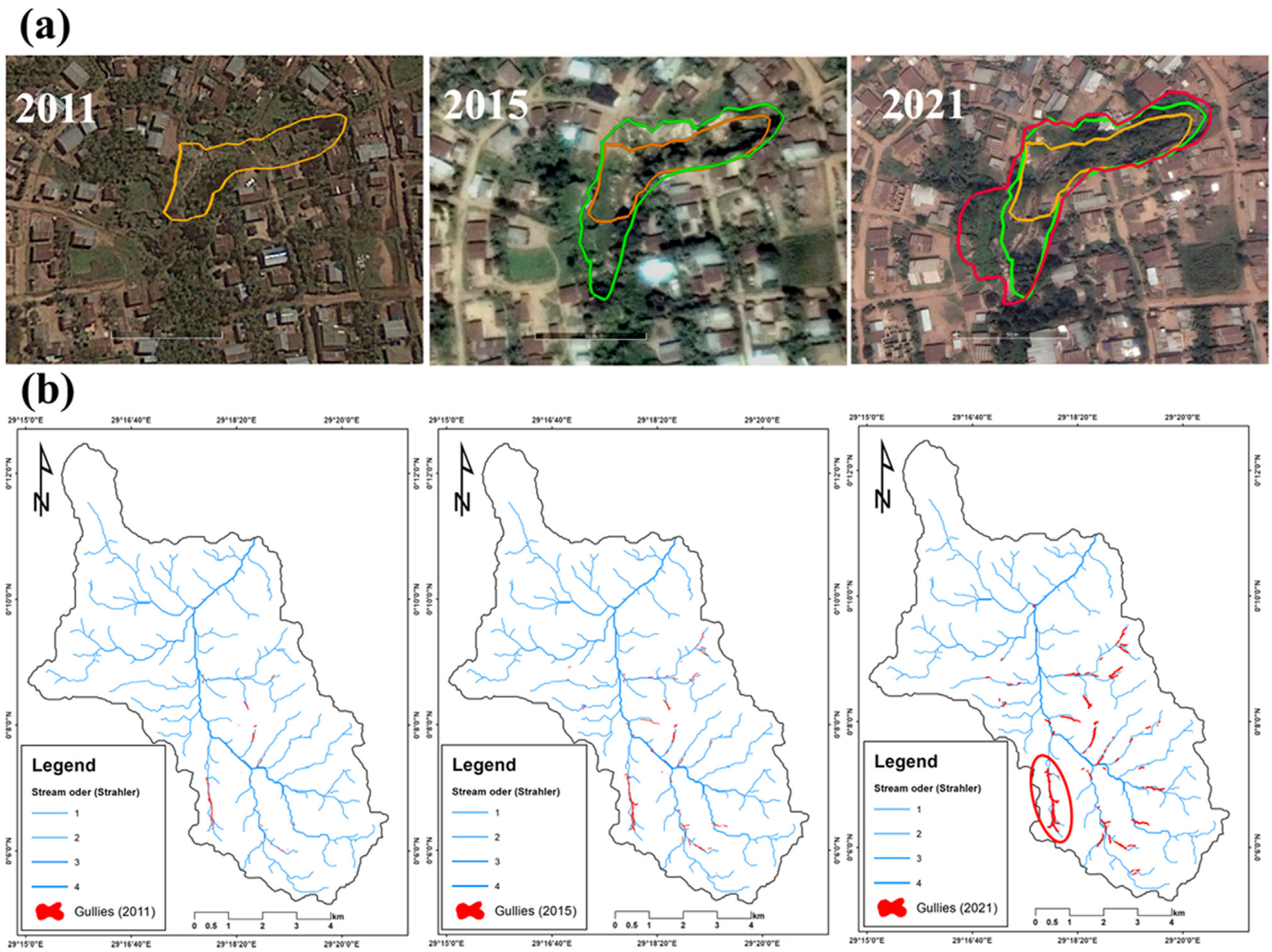

Fig. 5. Dynamics of gully erosion. (a) Dynamics observed on Google Earth images. The orange, green and red lines represent the gully extended in 2011, 2015 and 2021, respectively; (b) mapping of the gully network dynamics in 2011, 2015 and 2021. The gully circled in red is the largest gully in the Wayimirya Valley in 2021.

Fig. 6. Damages and economical losses caused by gully erosion expansion in the Kimemi watershed from (a) destruction of a bridge (b) commercial settlements, (c) gullying expansion, and (d) poor households' vulnerability increase.

(Fig. 8). Overall, the correlation between parameters was relatively higher in the grassland, bare land and building classes than in the woodland class. The adjusted R^2 value of the area-length regression was 0.8 while that of the area-width model was 0.68. It was noted by the scatter-plot distribution that these relationships were much stronger for small gullies than the biggest ones.

3.2. Factors of gully susceptibility in the Kimemi watershed

The effect of topographical, hydrological, climatic, and anthropogenic factors on gully susceptibility has been evaluated based on LRM. Initially the AIC of the full model was 122.6 but after the stepwise backward selection the AIC of the selected model reached 105.2. Among the 14 factors initially considered, the most significant group of influential factors included the slope at the gully head, SPI, LULC, NDVI, distance to roads, and distance to rivers. Areas with low slope (<10°) had high probability to gully occurrence than other areas (Fig. 9). Similarly, areas with high SPI values were more susceptible to being damaged by gully erosion. The probability of gully occurrence increased as an area was closer to roads and/or rivers. Finally, gully was more susceptible to occur in the class of bare land and building class compared to other classes.

4. Discussion

4.1. Dynamics of the gully process in the Kimemi watershed

The results of this study show that gully erosion in the Kimemi watershed was developed at a high rate between 2011 and 2015, followed by a relative slowdown between 2015 and 2021. The large differences in average annual growth rates during the study period might be

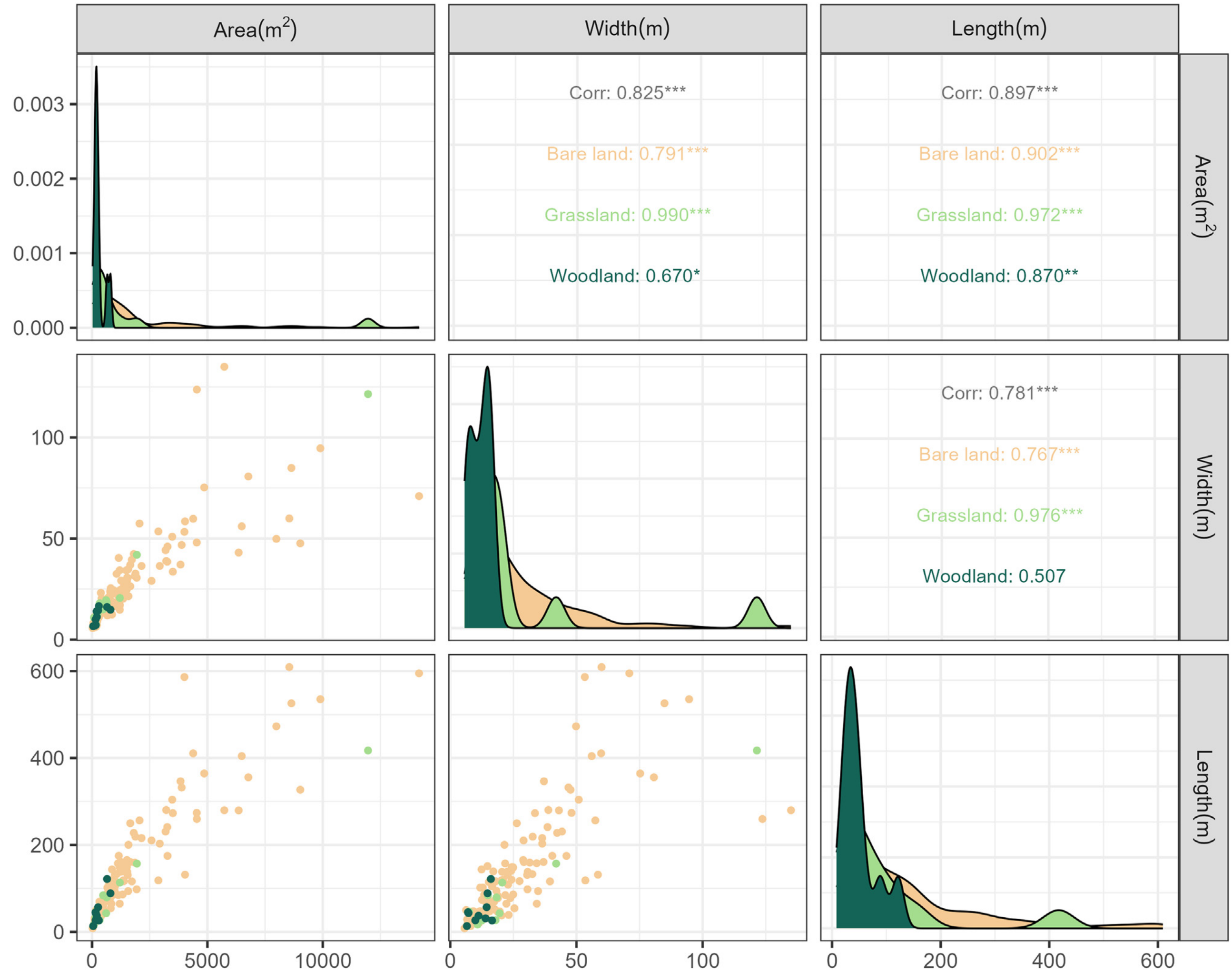

Fig. 7. Spearman correlation between gully morphological parameters in LULC classes.

explained by the natural cycle of gully development. The progress of gullies is very rapid during the juvenile stage and slows down with time (Sidorchuk, 2006; Makanzu Imwangana et al., 2015; Vanmaercke et al., 2016). Furthermore, the effect of rainfall should also be considered to explain this expansion over time of the gully network. Gully erosion is strongly correlated with the intensity of rainfall and the rainy season (Makanzu Imwangana et al., 2015; Vanmaercke et al., 2016). However, this variable was not taken into account in this study because of the lack of climate data to assess the effect of rainfall intensity on the gully expansion in this small urban watershed. Even though the lack of climate data, Sahani et al. (2012) found that the most high-day precipitation in Butembo area (1957–2010) is considered normal because its return period is less than six years. This author falls for the assumption that the main factors of the increase of runoff water related risks should be considered elsewhere than the climate.

The average gully density found in this study was 0.12 km/km^2 from 2011 to 2021. This gully density is intermediate based on the classification of Golosov et al. (2018). The value of the gully density found in this study is below the average for the city of Kinshasa where the density varied between 0.4 and 2 km/km^2 for the period 2006–2007 (Makanzu Imwangana et al., 2014). In a study quantifying the change in gully networks in arid regions (Northern Ethiopia), Frankl et al. (2013b) found a very high average density of 2.52 km/km^2 during the period 1960–2010. In the same region but a little further to east, Belayneh et al. (2020) found a consistently high density of around 1.87 km/km^2 in the Gumara watershed in Ethiopia. This high gully density obtained compared to that of this study can be explained by intense erosion activity in semi-arid and arid regions, as advocated by some authors (Frankl et al., 2012; Zakerinejad and Maerker, 2015).

This study indicates that the gullies increased in both length and width. The results show that both parameters can predict changes in the gully area. However, length is the best predictor. In view of the limited aims in developing countries, this work shows that length measurements can facilitate estimates of the degraded area. In the Kimemi watershed, the expansion of the gully network has resulted in an annual cumulated degraded area of 1.3 ha (2011–2015) and 1.1 ha (2015–2021) of land, with socioeconomic implications to the population living in this watershed (Fig. 6). According to Bartley et al. (2020), the destruction of houses, roads, and other infrastructure is a characteristic of the urban gully phenomenon. In 2021, almost a third of the land affected by the gully was located in the Wayimirya valley alone. The Warimirya gully was already identified by Sahani (2011) and occupied half of the volume of the few gullies investigated. Some factors amplify the gully phenomenon in this valley (Mukandala and Menomavuya, 2021). Among these factors, the construction of new buildings on the surrounding hillsides would have contributed to the increase in the runoff of water to this valley.

In the Kimemi catchment, significant changes in the evolution of gully morphological parameters are noted only in the bare land and building class. These results show that urbanization has influenced the gully process while suffering from damages. This urbanization phenomenon in the Kimemi watershed is globally marked by the increase in

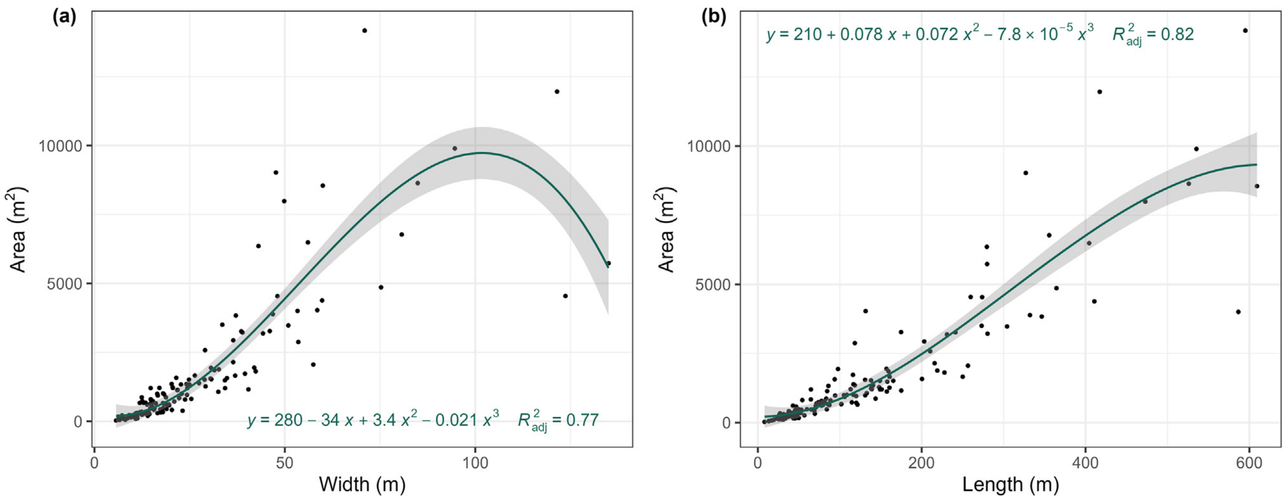

Fig. 8. Regression between (a) gully area and top width, and (b) gully area and length (with a total of $n = 148$ gullies).

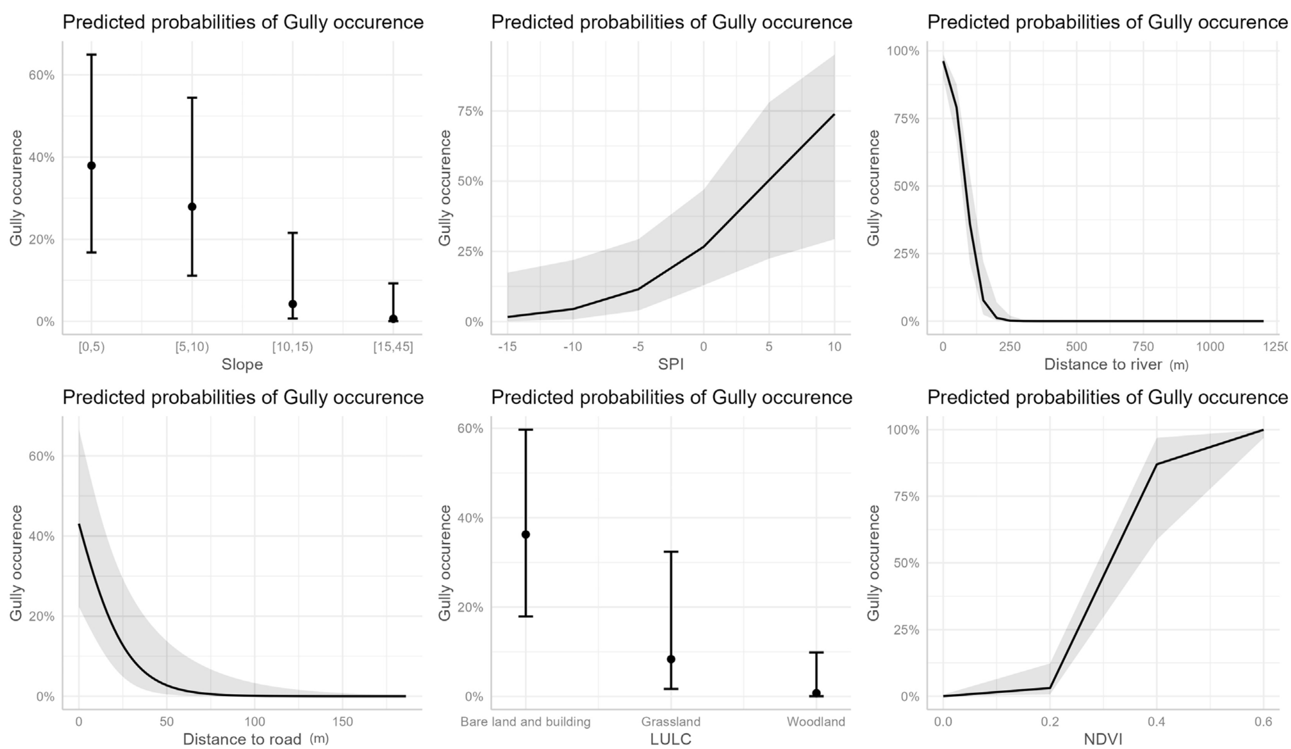

Fig. 9. Marginal predicted probability of gully occurrence for all factors in the selected model.

the surface area of bare land and building zones. The overall change rate of the bare land and building class was 29.8% from 2011 to 2015 and 2.1% from 2015 to 2021 (Mahamba et al., 2022). In addition, Sahani et al. (2014) argued that urbanization in Butembo in general has led to new land uses that have contributed to the appearance and evolution of gully erosion. Similarly, Mutungu et al. (2021) found out that the urbanization of the Kikwit town (DR Congo) has contributed to the formation and amplification of the gully. This observation remains valid in the city of Kinshasa where Makanzu Imwangana et al. (2015) also affirmed that the development of gullying is extended with the extension of the buildings.

4.2. Gully susceptibility in Kimemi watershed

Based on the LRM, factors influencing significantly the gully erosion susceptibility in the Kimemi watershed are the slope at the gully head, SPI, LULC, NDVI, distance to roads and distance to rivers (Table 2). These factors of gully occurrence in the Kimemi watershed can be combined into mainly, hydrological (distance to the river), topographic (slope and SPI), anthropogenic (distance to road, LULC) and environmental (NDVI). Therefore, the vulnerability of an area to gully erosion is explained by the topographic and hydrological configuration of the watershed exacerbated by human activities (Sahani, 2011).

Several studies have used the combination of slope gradient and contributing area to explain the topographic threshold for gully initiation (Gutiérrez et al., 2009; Samani et al., 2009; Makanzu Imwangana et al., 2014; Gudino-Elizondo et al., 2018; Yibeltal et al., 2019; Majhi et al., 2021). On the other hand, multiple indices were used to express the influence of topography on gully erosion (Conoscenti and Rotigliano, 2020). In this study, the effect of the topography was assessed based on the slope gradient and the SPI, which expressed the terrain configuration based on the contributing area. In the Kimemi watershed, gully

Table 2
Significance of the effects of the explanatory variables on the occurrence of gullying in the selected model.

Factors	Df	Deviance	AIC	LRT	Pr(>Chi)
Slope	3	103.7	117.7	18.5	0.0004***
SPI	1	91.9	109.9	6.7	0.0097**
Distance to river	1	207.1	225.1	121.9	0.0000***
Distance to road	1	99.6	117.6	14.4	0.0001***
LULC	2	96.6	112.6	11.4	0.0033**
NDVI	1	115.7	133.7	30.5	0.0000***

*, ** and ***: significant effect threshold α =0.5, 0.01 and 0.001, respectively. Df, degree of freedom; AIC, Akaike information criterion; LRT, likelihood ratio test; Pr (chi), *p*-value of chi-test.

erosion was more likely to occur in areas with high SPI values. These findings are similar to those reported by previous gully studies. According to Zakerinejad and Maerker (2015), the areas with high SPI values very often corresponded to large valleys with a large specific catchment area upstream. Similarly, Kakembo et al. (2009) found that the topographic areas most affected by gully erosion were those with high SPI values (in the range of 2–6) corresponding to areas with low slopes. This explains the fact that the large valleys are the most gullied. In fact, runoff water was concentrated in these areas creating new gully heads (Sahani, 2011).

In relation to land use classes, the results of this study reveal a high probability of occurrence in the class of bare land and building. These results corroborate those of Boughalem et al. (2020) who found that bare lands were more vulnerable to hydrological risks. This implies that any change in land use towards more bare land and building areas will increase vulnerability to gullying. Yet, this watershed was facing a rapid urbanization characterized by an increase in bare soil and built-up areas (Mahamba et al., 2022). As a consequence, the reduced infiltration of rain water into the soil generated increasing runoff and the risk of gullying.

Taking into account the factors, slope at the head of the gully, distance to roads and rivers, the results indicate that the gullying is more likely to occur in areas with low slope, close to roads and/or rivers. These findings are similar to those of Croke and Mockler (2001). These authors demonstrated that areas of road water released into the valley at bank level or on hillsides were most affected by gully erosion in the southeast region of Australia. Similarly, Sahani (2011) had already observed that roads played a prominent role in the initiation and development of some spectacular gullies in the city of Butembo. In fact, roads built generally without pavement contribute to changing hydrology of the Kimemi catchment and create gully erosion as in many other parts of the world (Poesen, 2018).

In particular, for roads, several studies have already demonstrated their effect on the occurrence and susceptibility to gully erosion following various methodological approaches. In Kinshasa, Kayembe and Wolff (2015) reported similar results to those obtained in this study. These authors pointed out that the orthogonality of the roads on the hillsides, and the pathways laid in the direction of the steep slope, accentuated erosion in the downstream areas. Nyssen et al. (2002) and Frankl et al. (2012) also demonstrated an increase in gully erosion after the construction of roads in the northern region of Ethiopia. Belayneh et al. (2014) stated the same conclusion in the Southern Region of Ethiopia along the Hadero Tunto-Durgi Road. In the Biram region (Iran), Rahmati et al. (2022) affirmed that the road construction was the main cause of gully formation. All these results support the conclusion that human activities strongly influence the gully erosion process (Castillo and Gómez, 2016).

4.3. Limitations of the study

Due to the lack of historical data on gully during the selected period, followed by insufficient financial and material resources, the data collection was limited especially for depth. This situation did not make it easy to understand the variations at the individual gully level and to assess the volume. In addition, the presence of vegetation in the gully can lead to underestimation/bias (Phinzi et al., 2021). Fortunately, some studies have shown that this underestimation is often only between 1% and 2% (Golosov et al., 2018). Despite the limitation comes from the lack of field measurements, Google Earth images have allowed us to highlight the large variations in the morphological parameters of the gully network over the entire watershed. The morphological parameters selected allowed us to understand the mainly *in situ* impacts.

Gully erosion is influenced by several factors (Valentin et al., 2005). However, this study considered 14 factors among which only 6 had influence significantly on gully susceptibility of lands in urban area. In addition, the low spatial and temporal resolution of data for some factors, especially rainfall and NDVI, would have influenced their effects on the dependent variable. Despite their small number, the selected factors allowed us to verify the hypothesis of the study. These factors allowed us to understand the effect of physical factors and anthropogenic developments on the susceptibility to gully erosion.

5. Conclusions

This study assessed the dynamic of the gully process as well as the factors of occurrence on the watershed scale. The findings reveal that gully erosion process in the Kimemi watershed follows a normal evolution cycle between 2011 and 2021; this is certified by high annual growth rates in the juvenile stage, followed by a slowdown over time. The area of degraded land has increased by a factor of four over the past decade, with annual losses of more than one hectare throughout the watershed. These changes are significant only in the class of bare land and buildings. This implies that while being impacted by gully erosion, anthropogenic infrastructures affect the process to some extent. This situation constitutes a challenge for sustainable urban development. Both topographic and hydrological factors increase the susceptibility of the land to gully. These factors are exacerbated by anthropogenic factors. Future research should focus on quantifying the socioeconomic impacts of this phenomenon in households and mapping vulnerable areas. Findings of this study provide valuable insights for decision-makers, who can use them to improve land use planning strategies and mitigate the effects of gully erosion.

Declaration of 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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.geosus.2023.07.001.

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