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Spatio-Temporal Erosion Modelling for Gullies Control in Kigali City: Case of Kigali Sector

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Abstract

Due to land scarcity, hilly topography, and the presence of a significant urban poor population in Rwanda, urban expansion driven by population growth in Kigali city has encroached upon vulnerable ecological areas, resulting in gully erosion. Given the intersection between erosion processes, urban dynamics, and specific locations in urban areas, monitoring temporal variations in erosion is essential for prioritizing resources for controlling gully in areas experiencing the highest erosion. This study aims to model the spatio-temporal patterns of soil erosion to support gully control efforts in Kigali, specifically focusing on the Kigali sector. Potential gully sites were identified using a Digital Elevation Model (DEM) and field measurements. The Integrated Valuation of Ecosystem Services and Tradeoffs-Sediment Delivery Ratio (InVEST-SDR) model was applied to quantify erosion intensity over the period from 2000 to 2022. Data analysis used Pearson's correlation to evaluate the relationship between estimated erosion levels and observed gully measurements. Zonal statistics analysis was conducted to assess the annual variation in soil erosion intensity at the cell level, aiming to identify areas prone to high erosion. The results indicate that both temporal and spatial erosion intensities increased during the 2010 period, rising to 43 and 150 tons/ha/year, up from 45 and 145 tons/ha/year in 2000. However, in 2015, these rates decreased to 38 and 103 tons/ha/year, before rising again in 2022 to 49 and 133 tons/ha/year. The results from field validation reveal a positive correlation (0.6) between gullies and soil erosion that is exacerbated by rapid urbanization. The findings and analytical approach of this study can support policy and decision-makers in developing cost-effective interventions to manage gullies and reduce soil erosion in the region most affected by soil degradation.

Keywords: InVEST-SDR**,** Spatio-Temporal Erosion Modeling, Gully, Urban Areas

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1. Introduction

Although urbanization plays a key role in enhancing socio-economic development and urban prosperity (UN-HABITAT 2016), uncontrolled urbanization also presents critical challenges in hilly urban regions of developing countries, leading to the formation of gullies and the loss of land (Das 2017; Junior et al. 2010; Mahamba et al. 2023a). Globally, over half of the world population resides in urban areas, with projections indicating that 90% will be in low- and middle-income countries. In countries with the limited land and undulating topography, like Rwanda, portions of the population are settled in high-risk zones, such as gully-prone areas, which expose urban livelihoods and the environment to natural hazards like gully erosion (Bai et al. 2017a; UN-DESA 2022). Gully erosion is one of the erosion processes caused by irregular, concentrated water flows during rainfall, which results in the removal of soil to significant depths (Ibrahim et al. 2017). Thwaites (2022) defines a gully as a long-lasting, narrow erosion feature typically deeper than 0.5 meters, with a steep head cut. It is formed by irregular water flows, often accompanied by rainfall. This erosion feature cannot be eliminated through traditional tillage practices and primarily erodes materials such as residual soils, unconsolidated materials, and saprolite—a type of rock that is weak and easily eroded by water runoff, excluding solid bedrock. The formation of a gully occurs when the erosive forces of soil exceed a certain threshold, leading to significant land degradation, reduced soil fertility, and disruption of land use. (Belayneh et al. 2014; Odongo 2017; Mahamba et al. 2023b). As mentioned by Sampaio et al. (2016) eroded soil can lead to adverse consequences such as urban flooding. If not consistently monitored, it becomes a significant threat to both urban infrastructure and agricultural land. Moreover, restoring severely degraded land can take decades, presenting a major challenge to sustainable urban development (Sampaio et al. 2016).

Though it was prioritized in the legal framework, ecological land degradation still occurs, particularly in the Kigali sector of the City of Kigali (CoK), due to the complexities of the urban system. In 2013, for instance, the CoK implemented the Kigali City Master Plan (KCMP), which was revised in 2020 to steer the city's development and future growth (Vetter-Gindele, et al.,2023; Baffoe, Manirakiza, Uwayezu, 2024; Uwayezu and de Vries, 2020). Nonetheless, due to the challenges associated with observing this guiding framework (City of Kigali 2020) and rapid urban population growth driven by large-scale rural-to-urban migration (Government of Rwanda 2008), informal urban development has occurred on marginal land, especially steep slopes, which are unsuitable for built-up. This, in

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turn, has contributed to increased gulling on the hillsides (Hitayezu et al. 2018), leading to soil erosion and posing threats to land and the environment downstream (Kabirigi et al. 2017a). The 2020 State of Erosion Control in Rwanda report indicates that the Kigali sector has been severely impacted by gullies, resulting in land loss due to the steep slopes, the presence of informal upland settlements, and the low adoption of urban farming terraces on the hillsides (Government of Rwanda 2022). This technical report also provides region-specific recommendations based on slope and land use types. Nevertheless, implementing these measures in urban areas alone is insufficient to sustainably address the root causes of gullies due to the rapid and uncertain pace of urbanization (Bai et al. 2017b). Consequently, there is a need for extra and tailored gully control strategies, focusing on the unique features and current conditions of each area (Marondedze et al. 2020).

Geospatial technologies and GIS-based erosion models have the potential to model both spatial and temporal erosion, providing valuable insights for planning and identifying the most effective strategies for urban gully control and management. Geographic Information System (GIS) provides a powerful tool for complex spatial data acquisition in gully-prone areas, modeling, and analysis of the results (Das 2017). Integrating GIS with erosion models such as the Integrated Valuation of Ecosystem Services and Tradeoffs- Sediment Delivery Ratio (InVEST-SDR) model enables the assessment of the impacts of land use over time and the effect of local conditions on erosion processes (Wachal 2007). By overlaying these results with a high-resolution Digital Elevation Model (DEM), gully channels can be modeled, providing valuable insights to support decision-making in erosion mitigation and gully control (Mitasofa 2013). Few previous erosion studies in Kigali have assessed erosion at the catchment scale, and there is a lack of spatial and temporal erosion assessments. This gap in knowledge hinders a comprehensive understanding of soil erosion evolution and impedes the development of informed policies and decision-making for soil conservation (Vijith et al. 2020). Model calibration remains challenging; thus, more frequent data collection is needed to validate model results and monitor erosion extent to enhance erosion mitigation strategies (Abdulkareem 2021; Igwe et al. 2017). Hence, this study aimed to integrate geospatial tools with the InVEST Sediment Delivery Ratio (SDR) model to analyze the spatiotemporal dynamics of soil erosion for gully control in Kigali, focusing on the Kigali sector. It specifically identifies the locations of potential gullies and quantifies the spatial and temporal intensity of soil erosion, considering the driving factors that emphasize the impact of rapid urbanization on erosion rates. The results of this study will assist land management authorities in selecting effective gully control and management approaches for areas with high soil erosion, which could ultimately contribute to enhanced ecological land conservation efforts.

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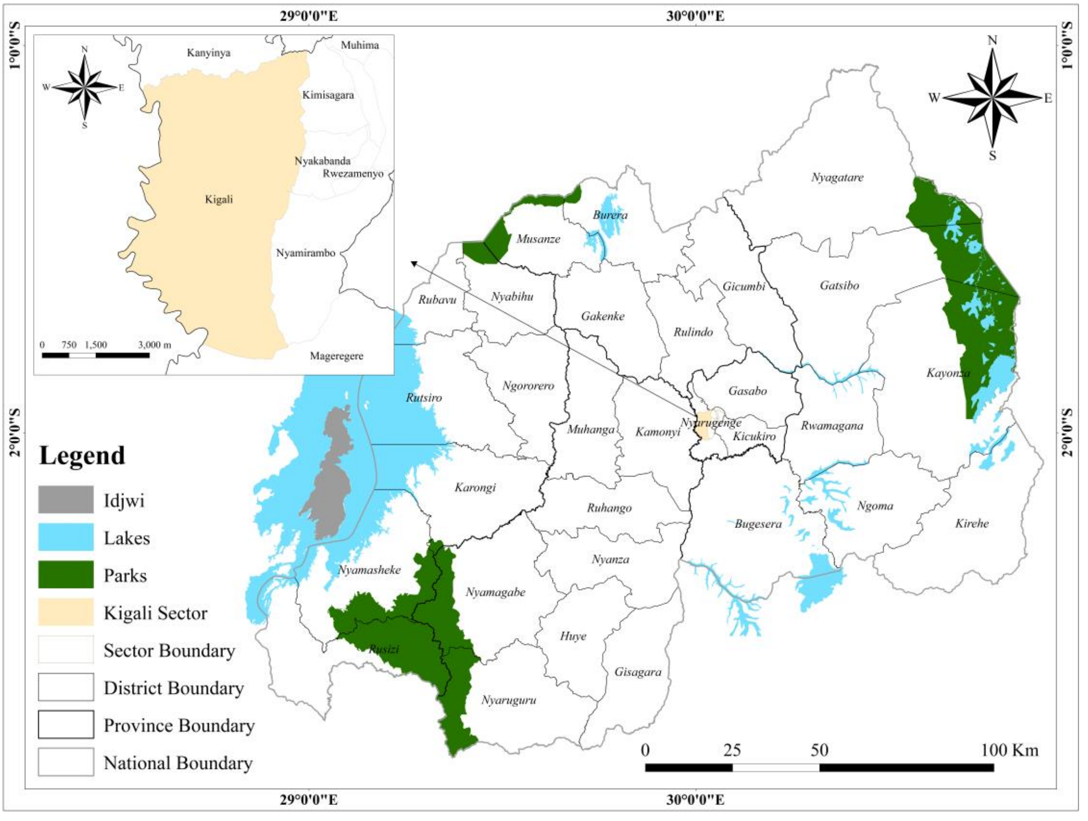
2. Materials and Methods

2.1. Study Area Description

The Kigali sector, covering an area of 2937.6 hectares, is situated at a latitude of 1°58’3.14” S and a longitude of 30°2’38.10” E. It is one of the sectors of the Nyarugenge district located in the periphery of Kigali city, part of the urban high land zone (Figure 1). The Kigali sector experiences rainfall throughout the year, with the main rainy seasons occurring from February to May and mid-September to December. Annual rainfall averages range between 1085.43 mm and 1115.54 mm, while the mean annual temperature is 26.6 °C. The geological composition largely includes loam, clay, clay loam, sandy loam, sandy clay, and silty clay.

Figure 1: Location of Kigali sector in the City of Kigali



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Due to the natural landscape and current environmental conditions of the Kigali sector, it was highly affected by gullies and soil erosion (Government of Rwanda 2022). Kigali sector has high undulating topography with more than half (56%) of the land having very steep slopes (>30%) and an elevation of 1800 m at Mt. Kigali and 1400m downstream which allows the soil to be eroded(City of Kigali 2010).

Given the rapid urbanization of the CoK, informal settlements are spreading along the non-buildable hillslopes of the Kigali sector (Dufitimana, et al., 2024; Hitayezu 2018). This trend affects other urban activities such as hillside urban agriculture, which is being conducted unsustainably, leading to gully formation and soil erosion (Government of Rwanda 2022). According to the Kigali City Detailed Master Plan Report for Nyarugenge District, Kigali was considered a greenfield area as of 2000 (City of Kigali 2010); however, it is now experiencing extensive development in its upland areas (Figure 2).

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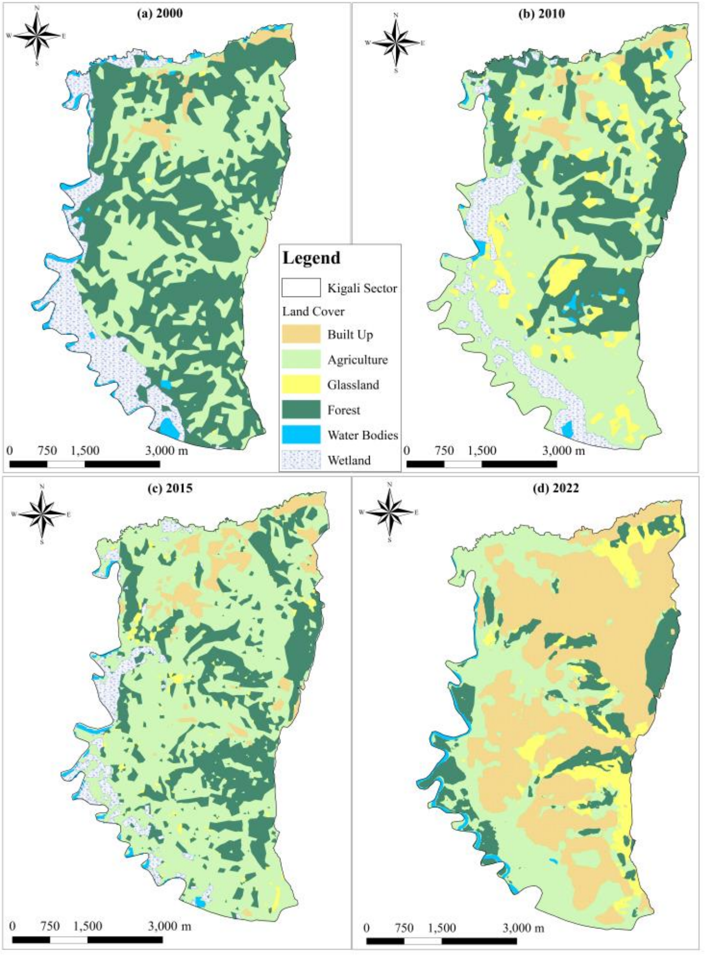

Figure 2: Land use land cover change in the Kigali Sector from 2000 to 2022

According to Figure 2, in 2000, urbanization covered only 2.1% of the area, with forests, croplands, and wetlands as the dominant land uses. However, by 2022, urbanization had surged to 30%, extending into areas prone to gully formation. This significant expansion prompted the selection of this region as a case study to examine how rapid urbanization affects soil erosion and to identify interventions policymakers should consider while promoting resilient urban development across Kigali. Therefore, spatial and temporal modeling of soil erosion for gully control in the Kigali sector could play a crucial role in supporting these efforts.

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2.2. Data Acquisition and Processing

Primary data were collected by surveying the study area through field observation and measurement. The Digital Elevation Model (DEM) was initially employed to identify potential gullies, which were later validated through field visits. A hand-held GPS was used to demarcate the boundary of the observed gullies by recording several points along the gully edges, while gully width and depth were measured with a tape meter, and gully length was calculated using ArcGIS software. This data was fundamentally collected to validate the predicted gullies and soil erosion. Secondary data were obtained through a desk review of government documents and other published materials. Since erosion modeling requires spatial data (Thomas 2018), additional data on rainfall, soil, topography, and land use/land cover were collected. These data were instrumental in determining rainfall erosivity, soil erodibility, the effects of slope length and steepness, supporting practices on slopes, and land cover management practices in the study area related to erosion. Table 1 provides a detailed description of the data and its sources.

Table 1: Description of Input data

Data	Source	Resolution
Administrative boundaries	UR-CGIS (University of Rwanda in the Centre of Geographic Information System)	1:1,411,968 scale
Rainfall for 2016	Rwanda Meteorological Agency	
Soil	UR-CGIS	
Digital Elevation Model (DEM)	NLA (National Land Authority)	10x10m
Land cover 2000,2010, and 2015	RCMRD (Regional Centre for Mapping of Resources for Development)	20 x20m
Land cover 2022	ArcGIS Living Atlas of the World	10 x10m

The collected spatial data was processed in ArcGIS Pro 3.0.1. The recorded gully points were imported into Google Earth Pro to digitize gully boundaries which were overlayed to the predicted gullies in ArcMap. Measured gully parameters were calculated in Microsoft Excel Office 2019.

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2.3. Data Modeling and Analysis

The potential gullies were modeled using a 10-meter resolution DEM and the hydrology tools in ArcGIS Pro. The initial stages of preparing this model generated three essential datasets, which facilitated further steps in delineating gullies within the study area. These datasets consist of the DEM, flow direction, and flow accumulation (Ikwuni 2013). The filled DEM was processed to eliminate any sinks in the original DEM. The flow direction was determined to identify the drainage patterns of the study area. Subsequently, flow accumulation was calculated to estimate the downward water flow into each cell (Domingue 1988). A raster calculator was employed to delineate streams by applying a threshold. Using the flow accumulation result, a threshold value of 1000 was assigned a value of 1 to distinguish streams from non-streams, with flow accumulation greater than the threshold indicating a stream, and values below it is representing non-stream areas. Those generated stream networks were linked, ordered, and converted into polyline features to delineate the gullies (Ikwuni 2013). These gullies threaten the land and make it less productive as they contribute to soil erosion(Nambajimana 2019).

The soil erosion modeling in the Kigali sector was based on the InVEST Sediment Delivery Ratio (SDR) model. This model needs input factors as for the Revised Universal Soil Loss Equation (RUSLE) Model that combines climate, soil, terrain, and land use and land cover parameters that correspond by: A= R*K*LS*C*P for quantifying annual average soil erosion; whereby A is a computed spatial average annual soil loss in ton/ha/year; R indicates the rainfall-runoff erosivity parameter (R-factor) which is measured in MJ mm /ha/h/year; K denotes the soil erodibility parameter (K-factor) which is expressed in ton h /MJ/ mm; LS represents the slope length (L) and slope steepness parameters; C expresses the land cover management parameter; and P is support-conservation practice factors. C, P, and LS parameters have unknown dimensions(Allafta & Opp 2022).

Rainfall erosivity of the Kigali sector was computed by using equation (1) and has been estimated for tropical areas (Karamage et al. 2016)

R= [38.46+ (3.48***P**) (1)

Whereby P represents the Mean Annual Rainfall in mm, whereas R is a computed rain-runoff erosivity factor. This average annual rainfall data was extracted from daily data in 2016 recorded by the Rwanda Meteorological Agency. Kriging interpolation was applied to generate a raster surface from point data. Subsequently, a raster calculator in ArcGIS Pro was used to create a rainfall erosivity map. The

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soil erodibility in the Kigali sector was estimated using a soil texture layer extracted from Rwanda's soil texture shapefile. A desk review was conducted to identify the k-factor values assigned to various soil textures. Table 4 presents the k-factor values used for the Kigali sector.

Table 2: Soil texture and its k-factor values

Soil Texture	**K-factor values (ton/ha)**
Loam	0.30
Clay	0.22
Clay loam	0.31
Sandy loam	0.09
Sandy clay	0.20
Sandy clay loam	0.20
Silt clay	0,58

Source: Thomas (2018)

The slope length (L) and slope steepness factor (S) for the Kigali sector were computed using a 10-meter DEM. This DEM was integrated into ArcGIS for processing, which included filling the DEM, and generating flow direction and flow accumulation, as was done in the hydrological modeling network (Khassaf et al. 2018). Equation (2), as used by Mitasova et al. (1996) was applied and processed in a raster calculator utilizing the map algebra tool within the GIS environment.

$$LS = \{(FA \times \text{Grid size})/22.1\}^{0.4} \times \{(\sin(\text{slope}) \times 0.01745)/0.09\}^{1.4} \quad (2)$$

LS represents the computed slope steepness and slope length; FA stands for Flow accumulation; and sin(slope) represents the sine of the slope, measured in degrees, derived from the filled DEM.

The land cover management factor (C-factor) for the Kigali sector was derived using the land use/land cover data for the city of Kigali from the years 2000, 2010, 2015, and 2022. C-factor values were assigned to the respective land cover classes based on previous studies.

https://dx.doi.org/10.4314/rjeste.v7i1.16

Table 3: Land cover classes of the Kigali Sector

Land Cover Class	C- Values
Forest	0.03
Open areas or class	0.1
Seasonal agriculture	0.03
Built up area	0.09
Water/wetland	0
Perennial agriculture	0.2

Source: (Karamage et al. 2016; Kabirigi et al. 2017b; Koirala et al. 2019)

The support practice factor (p-values) for the Kigali sector, contouring, has been adopted on the few sites that experience very steepness. Contouring values were used to assess its influence on soil erosion (Table 2).

Table 4: Slope Classes and corresponding p-values

Slope in %	Contouring Values
0-7	0.55
7-11.3	0.60
11.3-17.6	0.80
17.6-26.8	0.95
>26.8	1.00

Source: Koirala et al. (2019)

Slopes exceeding 26.8% were assigned a value of 1.00, as the majority of steep slopes in the Kigali Sector lack proper support and conservation practices, which is a key factor contributing to soil erosion in the study area (Kabirigi et al. 2017b; Byizigiro et al. 2020). The slope, ranging from 0% to 7 % was assigned 0.55 as this range represents lowland areas within the study region, characterized by wetlands and dense vegetation. These features help reduce surface water runoff by promoting infiltration and increasing land cover.

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2.4. Validation of Results

The results of the current study were compared with those of the previous one, and field visits were conducted to identify potential gully areas in the Kigali sector. Five potential gullies were then sampled for measurements to evaluate the relationship between soil loss and gullies. The width and depth of the observed gullies were measured using a tape measure, with each gully's cross-section divided into 3 or 4 subsections based on their dimensions and morphology to ensure precise measurement of height and width (both at the top and bottom) for each subsection. The average measurements were then calculated by utilizing the following formulas (Oparaku et al. 2018):

Average gully width = $\sum_{i=0}^{n}(Wb + Ws)/2$ (3)
Wb= $\sum_{i=0}^{n} Wb/n$
Ws= $\sum_{i=0}^{n} Ws/n$
Average gully depth = $\sum_{i=0}^{n} Dn/n$ (4)

The base width readings are represented by Wb, while Ws represents the shoulder width readings. The variable "n" indicates the number of intervals, and Dn refers to the depth of each interval. Measured gullies were also digitized and overlaid to the final soil erosion map to validate the final soil erosion rate. Pearson's correlation analysis, conducted in Excel, was then used to evaluate the relationship between the measured gullies and the amount of eroded soil.

3. Results and Discussion

3.1. Potential Gullies in the Kigali Sector

In the Kigali sector, which covers 2,937 ha, a total of 412 gullies, including rills, were identified. These gullies were categorized into four groups based on their length and are mostly located in areas of the hillside that have been impacted by human activities (Figure 3). Among the identified gullies, 152 have a total length of 5,390.86 m, 132 measure 21,539.37 m, 96 covers 9,941.09 m, and 32 spans 1,927.55 m. A study conducted by the Government of Rwanda (2022) found that by 2018, the Kigali sector had 300 gullies, including rills, across 2,299 ha, which represented 76% of the sector's land vulnerable to soil erosion. This increase in the

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number of gullies underscores the urgency of strengthening efforts to control and mitigate soil erosion.

3.2. Factors Influencing Gully Erosion in the Kigali Sector

Figure 4 highlights the key factors contributing to soil erosion in the Kigali sector. It demonstrates that all input variables of the InVEST SDR model played a role in determining the soil erosion rate, although some had a greater impact than others. The intensity of each factor's influence is represented by values ranging from 0 to 1, except for rainfall, which falls outside this range; higher values indicate a greater effect on soil runoff, and vice versa. Concerning rainfall erosivity in the Kigali sector, the highest R-factor value (1,115.54 MJmm/ha/h/year) was observed in the northwest, while the lowest value (1,085.43 MJmm/ha/h/year) was recorded in the southeast (Figure 4a). These values suggest that the rainfall intensity (below 1300mm) in the Kigali sector is not a major driver of soil erosion. However, when land use is poorly managed, this rainfall intensity can significantly contribute to soil runoff (Abdulkareem 2021; Igwe et al. 2017).

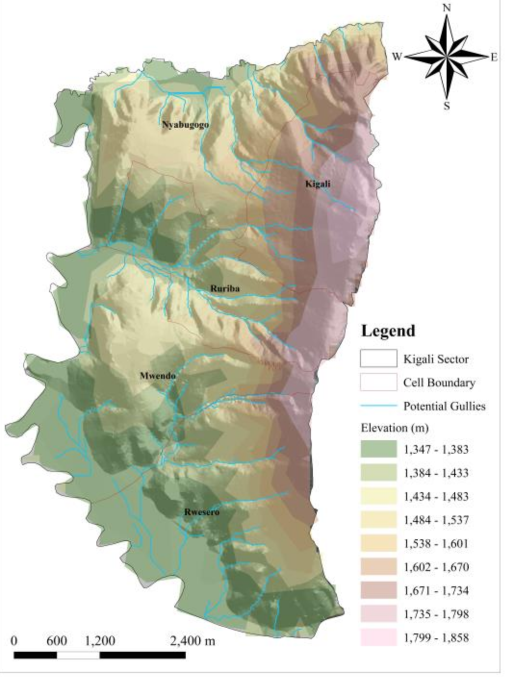

Figure 3: Predicted Gullies in the Kigali Sector

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The soil erodibility model results identify six classes of k-factor values, ranging from 0 to 0.58 t·h/MJ·mm (Figure 4b). Lower values were observed in areas with clay and sand-rich soils, such as clay and sand-clay, due to their high resistance to detachment, low susceptibility to erosion, and reduced runoff (Thomas 2018). In contrast, higher k-factor values correspond to areas with loam and silt-rich soils, which are more prone to erosion as they are less resistant to detachment and easily transported by rainwater droplets (Kim et al. 2006). As a result, high soil erodibility is prevalent in areas with loam and silt soils, primarily located in the northeastern part of the Kigali sector—a region affected by human disturbance.

Land cover management (c-factor) values range from 0 to 0.7. The lowest values are observed in forests, wetlands, water bodies, and well-managed urban areas, as these features play a pivotal role in reducing water runoff and controlling erosion when properly maintained (Karamage et al. 2016). On the other hand, the highest value of 0.7 is associated with areas that have low adoption of terracing on hillside farms (Kabirigi et al. 2017b), and degraded vegetation and forested areas around Mt. Kigali, where erosion is exacerbated by scattered upland settlements (Bizimana et al. 2020).

Higher p-factor values are concentrated on steep slopes and decrease as the slope becomes gentler (Figure 4). A p-factor of 1 was expected on steeper areas, as conservation and support practices were implemented only in small portions of land, while most of the area lacked such practices. In contrast, a p-factor of 0 was assigned to smaller areas where effective runoff management measures—such as rainwater harvesting systems and terraces—were in place, as well as to protected regions like wetlands and parts of Mt. Kigali (Gubic et al. 2020). Consequently, in the Kigali sector, key erosion factors—steep slopes, informal settlements spreading uphill, and limited use of urban farming terraces on slopes—had a notable impact, as shown in the LS-factor, C-factor, and P-factor maps.

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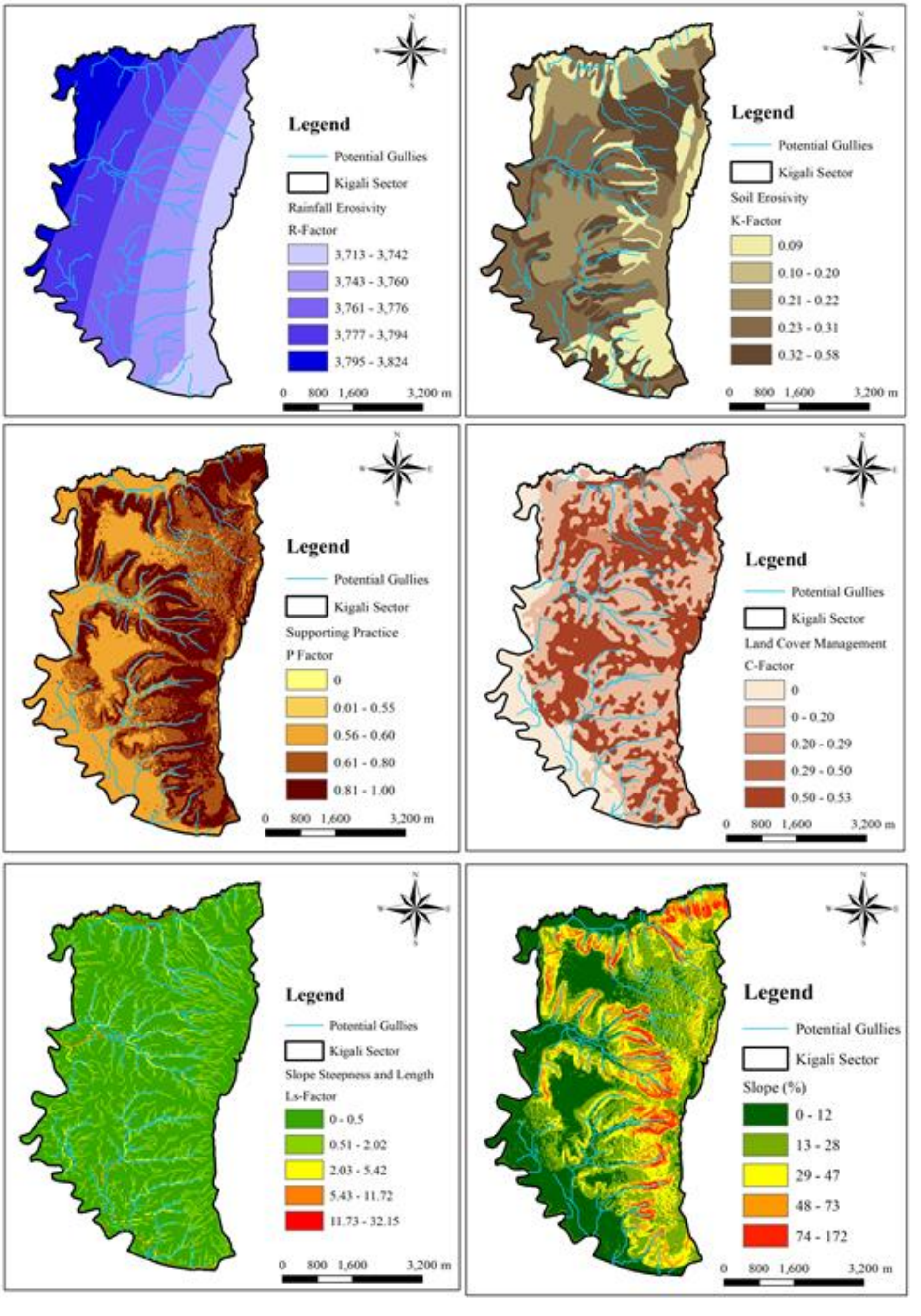

Figure 4: Factors of soil erosion in the Kigali Sector

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3.3. Soil Erosion in the Kigali Sector

The results of soil erosion modeling for the Kigali sector are illustrated in Figure 5. The highest rates of soil erosion, observed in gully-prone areas, range from 49 to 133 tons/ha/year. High erosion rates fall between 31 and 49 tons/ha/year, moderate rates between 17 and 31 tons/ha/year, low rates from 5 to 17 tons/ha/year, and very low rates range between 0 and 5 tons/ha/year. A comparison with previous studies shows that these findings align with existing trends. For example, the findings observed by Bizimana et al. (2020) , in their study on "Cadastral Information and Erosion Modeling for Monitoring Gullies in Mpazi Catchment," reported annual averages ranging from 100 to 150 tons/ha/year. Similarly, Irankunda Moise (2021) found comparable erosion rates exceeding 99 tons/ha/year in the nearby Yanze watershed, which is close to the Kigali sector.

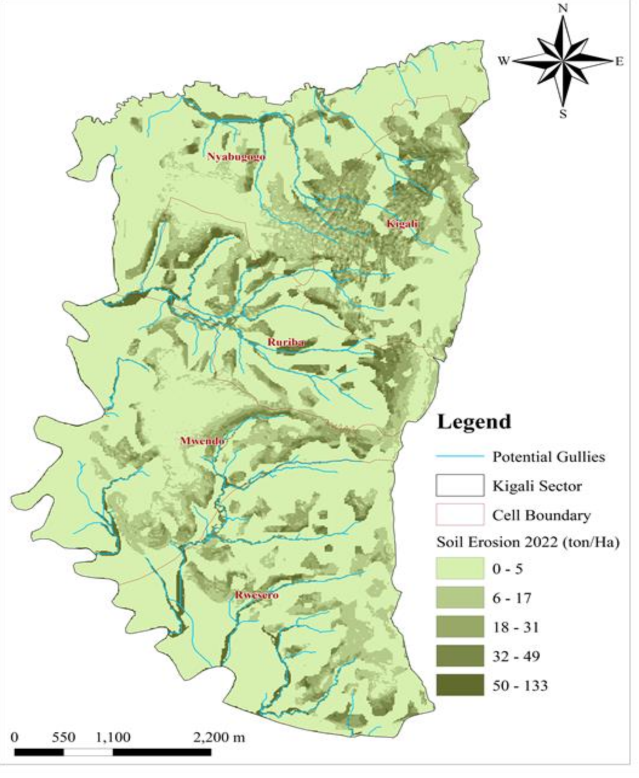

Figure 5: Soil erosion rate in the Kigali Sector by 2022

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Figure 6 shows the spatio-temporal evolution of soil erosion trends in the Kigali sector from 2000 to 2022. A notable increase in erosion rates occurred in 2010, reaching 43 and 150 tons/ha/year from the baseline rates of 45 and 145 tons/ha/year which was counted in 2000. By 2022, erosion rates had further escalated to 49 and 133 tons/ha/year, compared to 38 and 103 tons/ha/year in 2015. As shown earlier om Figure 2, which highlights land use change analysis from 2000 to 2022, this increase is largely attributed to the expansion of urban cropland in 2010 and the rapid expansion of built-up areas on marginal land with steep slopes in 2022, which accelerated soil erosion (Government of Rwanda 2022).

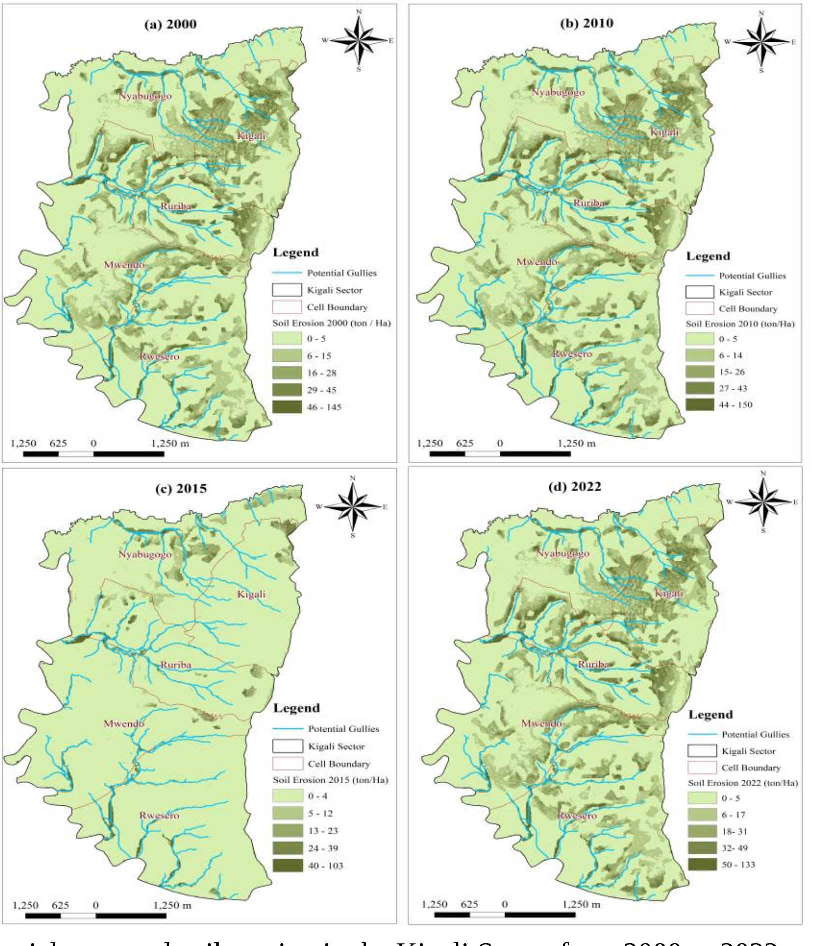

Figure 6: Spatial-temporal soil erosion in the Kigali Sector from 2000 to 2022

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The analysis of soil erosion trends from 2010 to 2015 shows a significant reduction in erosion levels. This reduction is probably due to strong political commitment demonstrated through the implementation of environmental policies and law enforcement intended to mitigate soil erosion in susceptible zones of the CoK, including the Kigali sector. Remarkable interventions during 2015-2016 involved the CoK, in collaboration with the Rwanda Environmental Management Authority (REMA), which focused on regenerating and rehabilitating degraded ecological landscapes like wetlands. This included relocating urban activities and settlements from ecologically sensitive areas to more suitable sites, thereby protecting and conserving the natural environment to strengthen urban resilience against global shocks (Gubic et al. 2020). More detailed information on these efforts can be found at www.shiftcities.org/post/restoring-kigalis-wetlands-accelerate-climate-resilience. These initiatives extended to other vulnerable areas, including steep slopes, where tree planting and forest protection were undertaken to prevent soil erosion. These measures have been particularly beneficial for the Kigali sector, partially stabilizing areas like Mount Kigali's steep slopes and conserving wetlands, all of which contributed to the reduction of soil erosion by 2015. Nevertheless, despite these positive developments, soil erosion intensity has recently been rising due to ongoing urban growth. To accurately identify high-priority intervention areas, zonal statistics were calculated in ArcGIS Pro 3.0.1 by overlaying cell boundaries within the sector onto soil erosion maps for the years 2000, 2010, 2015, and 2022. Table 5 provides soil erosion rates per cell unit in the Kigali sector, reflecting the overall erosion rate across the 2000-2022 period.

Table 5: Average soil erosion rate per Cell between 2000 and 2022

N/S	**Cell**	**Area (Ha)**	**Annual Mean Soil Erosion (tons/year)**			
			Year-2000	Year-2010	Year-2015	Year-2022
1	Kigali	433.7	117.0	107.2	7.5	23.6
2	Mwendo	691.6	66.5	69.3	4.8	41.4
3	Nyabugogo	618.7	43.5	68.0	26.6	27.1
4	Ruriba	425.0	68.5	67.0	7.6	59.9
5	Rwesero	768.6	35.7	61.9	0.7	38.8
	Total	**2937.6**	**331.1**	**373.4**	**47.3**	**190.7**

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3.4. Annual Variation of Soil Erosion in the Kigali Sector

The vertical bar plots in Figure 7 demonstrate the annual variation in soil erosion intensity at the cell level within the Kigali sector. The black bar represents erosion intensity in 2000, the orange bar corresponds to 2010, the grey bar indicates 2015, and the yellow bar shows the intensity in 2022. Longer bars indicate higher erosion intensity. The data reveals an increase in erosion intensity in 2010 and 2022, while a decline was observed in 2015. The highest erosion intensity in 2022 was observed in Ruliba Cell, followed by Mwendo Cell, both located in built-up and urbanized agricultural areas. Although other villages experienced low to moderate erosion with an overall decline, Rwesero Cell, situated in another urbanized area within the sector, saw an increase in erosion intensity.

Previous studies have proven the linkage between urbanization and soil erosion in urban areas. For instance, Aswathy et al. (2013) show that urbanization accelerates soil erosion as a result of the expansion of built-up areas, which transforms natural ecosystems into economic-focused land uses. Alike, McGrane (2016) emphasizes that the uncontrolled expansion of urban areas, driven by increasing population demands, leads to greater exploitation of natural resources, reducing urban resilience and resulting in soil erosion.

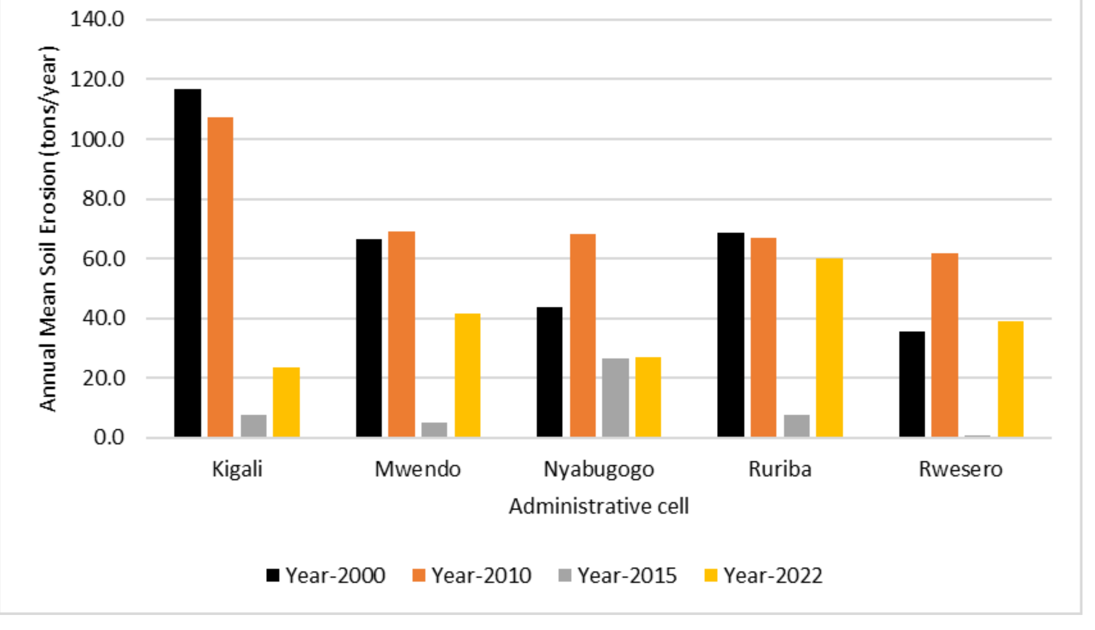

Figure 7: Average soil erosion rate from 2000 to 2022 per Cell

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Despite recent research, a strong correlation between soil erosion and uncontrolled urbanization remains evident. For instance, Polovina et al. (2021), demonstrate that addressing the challenges of rapid urban population growth has led to extensive clearing of new areas in hazardous zones. This trend poses a significant problem in many developing cities, resulting in exacerbated soil erosion and subsequently damaging urban functionality. Also, Mufungizi et al. (2024) found that unplanned urbanization both influences and is influenced by soil erosion processes. In such scenarios, individuals often exploit urban resources, specifically land, in an unsustainable manner, thereby exposing urban livelihoods to environmental shocks like soil erosion.
Whenever rapid, uncontrolled urbanization occurs in land-scarce regions with hilly topographies, it creates conditions conducive to the formation of gullies on slopes. This leads to intensive soil erosion, which adversely affects city development (Das 2017; Junior et al. 2010; Mahamba et al. 2023a). In the context of Kigali, which has experienced these issues, it is recommended that land and environmental authorities implement targeted gully control strategies in areas identified as having the highest and increasing levels of soil erosion. Such measures are essential for mitigating urban erosion and supporting sustainable city development.

3.5. Validation of Results

The field measurements for the sampled gullies revealed dimensions as follows: gully 1 measured 1.6 m in width and 1.9 m in depth; gully 2, 1.8 m in width and 1.1 m in depth; gully 3, 6.5 m in width and 2.1 m in depth; gully 4, 5.0 m in width and 4.5 m in depth; and gully 5, 3.0 m in width and 1.5 m in depth. Using these measurements alongside the lengths of each gully calculated in ArcGIS, the estimated volume of soil erosion was determined to be 583.7 m³ for gully 1, 1104.2 m³ for gully 2, 20639.9 m³ for gully 3, 9122.5 m³ for gully 4, and 5738.0 m³ for gully 5. Results from Pearson's correlation analysis indicate a positive relationship between gully width, depth, and the volume of eroded soil, with larger gully dimensions associated with increased soil erosion. Table 6 presents the correlation between these variables.

Table 6: correlation between measure gullies and soil erosion rate

	Measured Gullies (m)	*Eroded Soil (m3)*
Measured Gullies (m)	1	
Eroded Soil (m3)	**0.6**	1

Source: Data analysis

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Table 6 shows a positive correlation (0.6) between gully formation and soil erosion, indicating that gully development is closely linked to soil erosion in the Kigali sector. This linkage was confirmed by observations of actual gully measurements in areas predicted to have high to very high soil erosion values (Figure 7). Figure 7 further illustrates the impact of gully presence on predicted soil erosion levels within the Kigali sector, based on sampled gullies located in high soil erosion zones. Consequently, implementing gully erosion control measures in these areas, particularly in zones identified as having the highest soil erosion risk, could be beneficial in mitigating erosion.

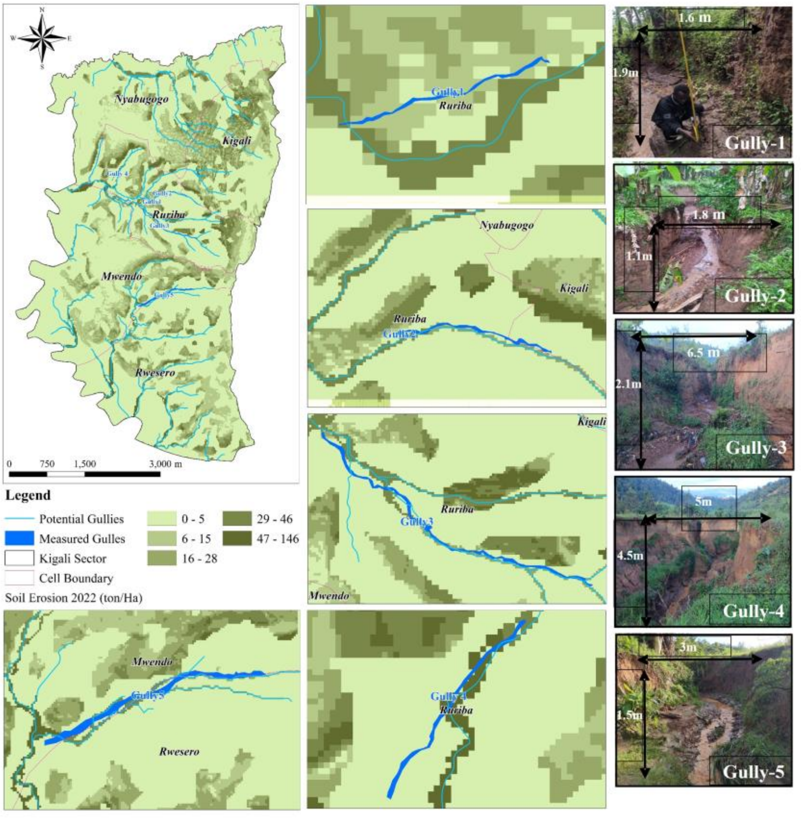

Figure 8: Location of measured gullies in the Kigali Sector

3.6. Policy Implication

The development of gullies due to severe soil erosion in the Kigali sector is closely linked to gaps in policy enforcement intended to protect areas at high risk of

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erosion, particularly on steep slopes exceeding 30%, from urban encroachment. Since 1966, the Government of Rwanda has introduced several national programs to control soil erosion. However, erosion remains a persistent issue in hilly urban areas of Kigali, including the Kigali sector (Kabirigi et al. 2017b). For example, Rwanda's National Land Use and Development Master Plan 2020-2050 restricts the development of settlements and other unsuitable activities on slopes greater than 30%. For slopes over 50%, tree planting, suitable crop cultivation, and runoff control measures are recommended instead (Government of Rwanda 2022). To ensure compliance with these guidelines at the community level, local districts were advised to create detailed physical plans to help guide local actions (Government of Rwanda 2012). However, while the Kigali sector does have such a plan, evidence from satellite and aerial imagery, corroborated by field visits, reveals that steep hillsides over 55% are still encroached by informal settlements and urban activities, with limited implementation of erosion control measures. The lack of zoning regulations enforcement has led to irrational land use, such as the informal settlements development and hillside farming without terraces. The combination of informal hillside settlements and unregulated farming on steep slopes has accelerated soil erosion and gully formation (City of Kigali 2020; Nyiransabimana, et al. 2019). Therefore, strengthening awareness and enforcement of land policies, along with regular monitoring, is vital to address these challenges.

4. Conclusion

Gully erosion in Kigali city varies across different regions and periods, displaying distinct patterns of erosion intensity. The ongoing urban gully erosion has been exacerbated by the expansion of urban development into high-risk areas, which increases exposure to severe soil erosion. To effectively manage and mitigate these gullies, a local understanding of ecological landscape dynamics is essential. Since gully erosion is influenced by both geographic location and seasonal factors, obtaining reliable data is crucial for addressing its underlying causes. In this study, maps of gully locations and erosion intensity were created for urban areas, providing a comprehensive tool to analyze the complex urban systems linked to erosion variability. A geospatial-erosion modeling approach, supported by field measurements, was applied to produce these maps. They provide guidance for developing targeted measures to control gullies and reduce soil erosion in areas with high erosion levels. The findings underscore the need for regular monitoring and allocation of resources to improve the implementation of erosion control strategies in identified erosion hotspots. By generating maps of gully locations and soil erosion, this study aims to guide decision-makers in prioritizing cost-effective interventions suited to each erosion-prone zone.

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The results indicate that the Kigali sector had 412 recorded gullies, showing a positive correlation (0.6) with soil erosion, which varied significantly by period and location. Erosion rates rose from 43 to 150 tons/ha/year in 2000 to 45 to 145 tons/ha/year in 2010 and further increased to a range of 49 to 133 tons/ha/year in 2022 due to the expansion of croplands and built-up areas on steep slopes. A remarkable reduction in erosion was observed in 2015, with rates decreasing to between 38 and 103 tons/ha/year, attributable to policy enforcement efforts aimed at restoring degraded landscapes and protecting critical natural resources within Kigali, including wetlands and hilltop forests. However, erosion has resurged recently, driven by the intensified urban expansion. Unprotected steep slopes subject to gully formation, mainly driven by informal urban developments such as unterraced settlements and urban agriculture, are identified as key contributors to ongoing soil erosion in the study area.

This calls for strategic urban growth management in Kigali to guide development toward stable areas, minimizing impacts on vulnerable ecological zones. To enhance the resilience of planned developments, integrating green infrastructure and prioritizing ecological considerations within urban plans and programs are essential to mitigate the effects of urbanization on soil erosion. Implementing water runoff management strategies, such as contour terracing on slopes, checking dams in gully channels, and other nature-based solutions (e.g., rainwater management at the source), can also boost land productivity and help withstand environmental and climate-related challenges. Findings from this study provide valuable insights for policymakers and urban planners, emphasizing the need to incorporate gully erosion management into sustainable urban development strategies. Given the effectiveness of the InVEST model in quantifying landscape changes and their impacts on urban systems, this approach could be beneficially extended to other regions with ecological data but limited financial resources, supporting improved soil conservation planning and management in developing countries.

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