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Assessing Flood Vulnerability Zones and Their Driving Factors to Guide Community-Based Resilience Planning Across Ngororero District, Rwanda

Rebecca Walker[1], Dr. Richard Mind'je[1] (PhD), Lucia N. Yeenee[2] & Dr. Samuel Gad Habarurema[3] (Msc, MA, MD, PhD)
[1]Faculty of Environmental Studies, University of Lay Adventists of Kigali, Kigali, Rwanda
[1]Faculty of Environmental Studies, University of Lay Adventists of Kigali, Kigali, Rwanda
[2]Faculty of Environmental Studies, University of Lay Adventists of Kigali, Kigali, Rwanda
[3]Southern New Hampshire University, Manchester, USA

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Abstract

Floods are recognized as devastating and deleterious natural disasters which are contemporary substantial threats to communities, exerting profound impacts on human lives, infrastructure, and the environment. Hence, the aims of this research were to assess and map the flood vulnerability zones, determine the primary local factors driving flood vulnerability, and evaluate the existing flood mitigation measures and propose evidence-based recommendations for enhancing community-based flood resilience. Using an integrated approach, this study combined remote sensing, Geographic Information Systems (GIS) techniques and expert knowledge, to map and model flood vulnerability zones, determining the risk levels using the AHP model considering a set of driving independent variables including elevation, slope, rainfall, land use/land cover (LULC), soil type, distance to streams, distance to roads, flow accumulation, and topographic wetness index (TWI). The results of the study for the first objective showed that 66.6% of the area classified as very high and high vulnerability zones, mainly in the northern and north-western regions. Moderately vulnerable areas covered 18.1%, predominantly in the southern and central parts, while low and very low vulnerability zones comprised 15.3%, mainly in the central and north-eastern regions. This highlights the heterogeneous distribution of vulnerability across the district, emphasizing the need for tailored mitigation strategies. The results of the second objective revealed rainfall (26.7%), proximity to rivers (21.4%), flow accumulation (13.3%), and LULC (12.5%) as the most influencing factors to flood vulnerability in the study area. In addition, the soil texture (9.4%) and elevation (8.2%) exhibited moderate influence, while TWI (4.1%), proximity to roads (2.8%), and slope (1.6%) disclosed a low influence. Understanding these factors enables prioritization of mitigation efforts, focusing on addressing rainfall patterns and proximity to rivers. The third objective suggested sustainable land management practices such as afforestation, agroforestry, terracing, and engineering strategies such as dam construction, resilient drainage systems in addition to strengthening early warning systems as measures that can help in flood vulnerability reduction. Thus, integrating ecosystem-based, infrastructure-based, and community-based measures is crucial for reducing flood vulnerability in Ngororero District, Rwanda.

Keywords: *Community Resilience, Flood Vulnerability, GIS, Ngororero District, Remote sensing.*

1. Introduction

The Ngororero district in Rwanda, marked by its diverse topography and socio-economic characteristics, confronts recurring challenges associated with the frequency and severity of floods. Existing research, exemplified by studies such as Uwizeyimana et al. (2019) and Nkurunziza et al. (2023) have shed light on the dynamics of flood vulnerability in Rwanda and, more specifically, within the Ngororero district. However, these studies have yet to comprehensively integrate the factors contributing to the frequency and severity of floods in the district, leaving a critical gap in understanding the holistic implications of topography, land cover, and socio-economic factors on the recurrent flooding events.

The frequency and severity of floods in Ngororero district, as witnessed and reported in recent years, necessitate an urgent and targeted investigation into the underlying causes of vulnerability (Nkurunziza et al., 2023). Recent research conducted by Adebayo et al. (2022) and Victor et al. (2023) have indicated a pressing need to assess and understand the specific factors driving the elevated vulnerability to floods. While natural factors such as topography and climate play significant roles, socio-economic factors also contributing to the heightened susceptibility of communities in the district. The need for a comprehensive assessment becomes paramount in developing a nuanced understanding of the intricate interactions among these factors and formulating effective strategies for mitigating the impact of floods. Furthermore, there is an evident gap in the implementation of community-based resilience planning initiatives specific to the Ngororero district owing to the lack of scientific evidence-cantered research baseline.

The existing studies provide foundational insights but fall short of providing a tailored framework for community-based resilience planning that addresses the unique challenges posed by floods in this specific locale (Adebayo et al., 2022). A lack of evidence-based, high-resolution understanding of locally prevailing flood vulnerabilities hinders development of well-targeted community resilience strategies and integrated risk reduction plans. National hazard risk models do not provide the hyperlocal vulnerability insights at appropriate community scales needed to catalyse preparedness and drive local ownership over solutions. Without addressing these knowledge gaps surrounding specific risk factors across Ngororero district, even well-intended resilience planning measures will fail to match actual on-the-ground conditions facing residents most exposed or susceptible to potential flooding disaster impacts. Thus, this research will aim to address these identified gaps and contribute vital knowledge that can guide the development of comprehensive and context-specific community-based resilience planning initiatives in the Ngororero district.

1.1 Research Objectives

1.1.1 General objective

The general objective was to assess flood vulnerability zones and their driving factors to guide community-based resilience planning across Ngororero district, Rwanda.

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1.1.2 Specific objectives

The specific objectives of this study are the followings:

(i) To identify flood vulnerable zones within the Ngororero district

(ii) To assess the main influencing factors contributing to flood vulnerability in Ngororero district

(iii) To evaluate the existing flood mitigation measures and proposes evidence-based recommendations for enhancing community-based flood resilience.

2. Materials and methods

2.1 Profile of Musanze District

Ngororero district, located in Rwanda's Western Province, covers 679 km² and comprises 13 sectors, 73 cells, and 419 villages. Characterized by high mountains and steep slopes, it ranges in altitude from 1,460 m to 2,883 m. The climate is tropical with four seasons, facilitating agriculture across its twenty swamps totaling over 1000 ha. The region experiences regular rainfall averaging 1527.7mm annually, enabling three agriculture seasons: A (short rainy), B (long rainy), and C (long dry).

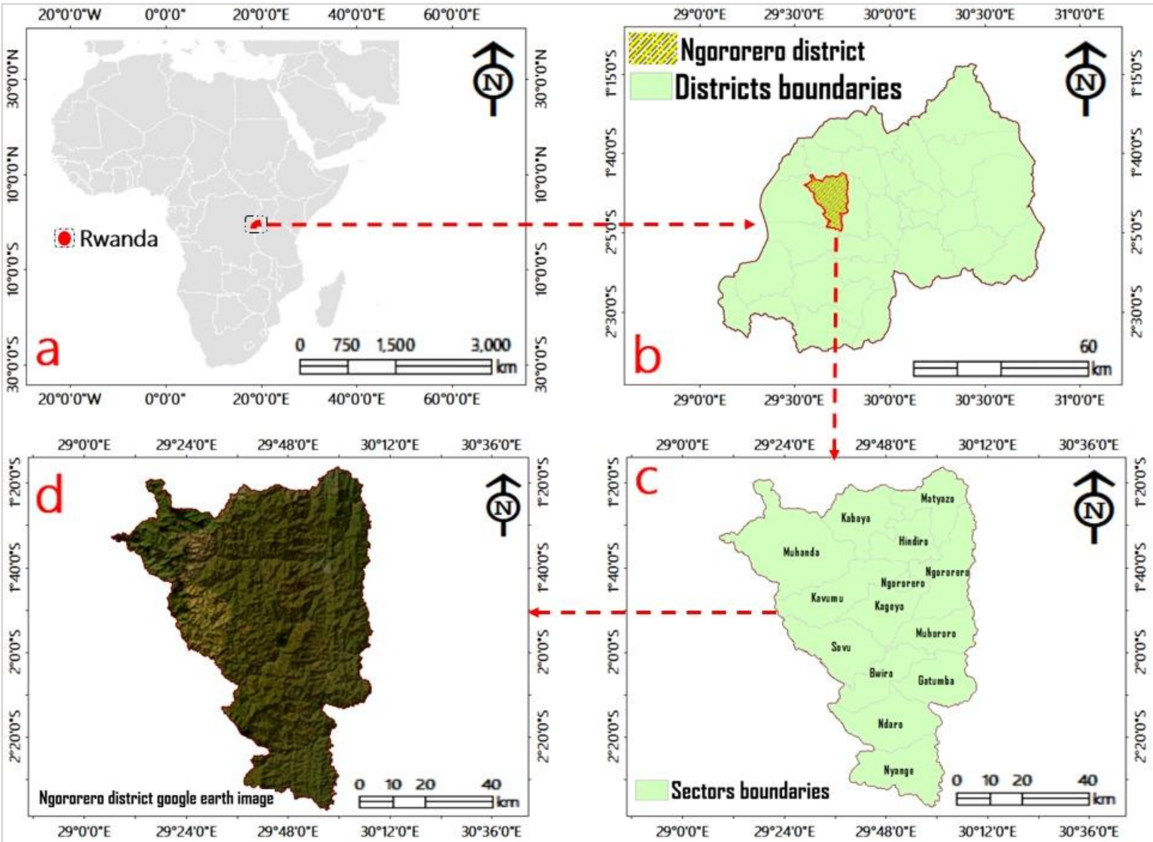

Figure 3.1: Geographical location map of the study area; (a) location of Rwanda at continent level; (b) location of Ngororero District at national level; (c) the sectors subdivisions in Ngororero District; (d) The google earth map representation of Ngororero district

2.2 Research design and data collection methods

The research design adopted a cross-sectional quantitative approach to assess flood vulnerability in Rwanda's Ngororero District. It involved comprehensive data collection, including administrative and raster data from satellite images, to analyze flood vulnerability zones and driving factors. Data processing utilized the Analytical Hierarchy Process (AHP) within Geographic Information Systems (GIS) to prioritize factors. Data collection methods encompassed field surveys, remote sensing techniques, and qualitative document analysis to gather both quantitative and qualitative data.

Table 3.1: Ordinal scale represents preference of judgment

Ordinal scale	Degree of preference	Remarks
1	Equally	Factors inherit equal contribution
3	Moderately	One factor moderately favored over other
5	Strongly	Judgment strongly favor one over other
7	Very strongly	One factor very strongly favored over other
9	Extremely	One factor favored over other in highest degree
2,4,6,8	Intermediate	Compensation between weights 1,3,5,7 and 9
Reciprocals	**Opposite**	**Refers inverse comparison**

Source: Saaty (1990)

Table 3.1 presents an ordinal scale representing the preference of judgment based on Saaty, (1990) Analytical Hierarchy Process. The scale ranges from 1 to 9, with 1 indicating equal preference, 9 indicating extreme preference, and intermediate values (2, 4, 6, 8) representing varying degrees of preference. Reciprocals are used to denote opposite comparisons. This scale facilitates the assessment of factors based on their relative importance, aiding decision-making processes in the research context.

Table 3.2: Random consistency index (RI)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Source: Saaty (1990)

Table 3.2 displays the Random Consistency Index (RI) values proposed by Saaty (1990) for different numbers of criteria (N) in the Analytical Hierarchy Process (AHP). RI serves as a reference point for assessing the consistency of pairwise comparisons made during the AHP. The RI values correspond to specific N values, indicating the maximum acceptable inconsistency threshold. Researchers compare their consistency ratio (CR) against these RI values to ensure the reliability of their judgments and maintain consistency throughout the decision-making process. For this research, Random Consistency Index values provide benchmarks to evaluate the consistency of pairwise comparisons made during the Analytical Hierarchy Process.

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2.3 Illustration of research methodology

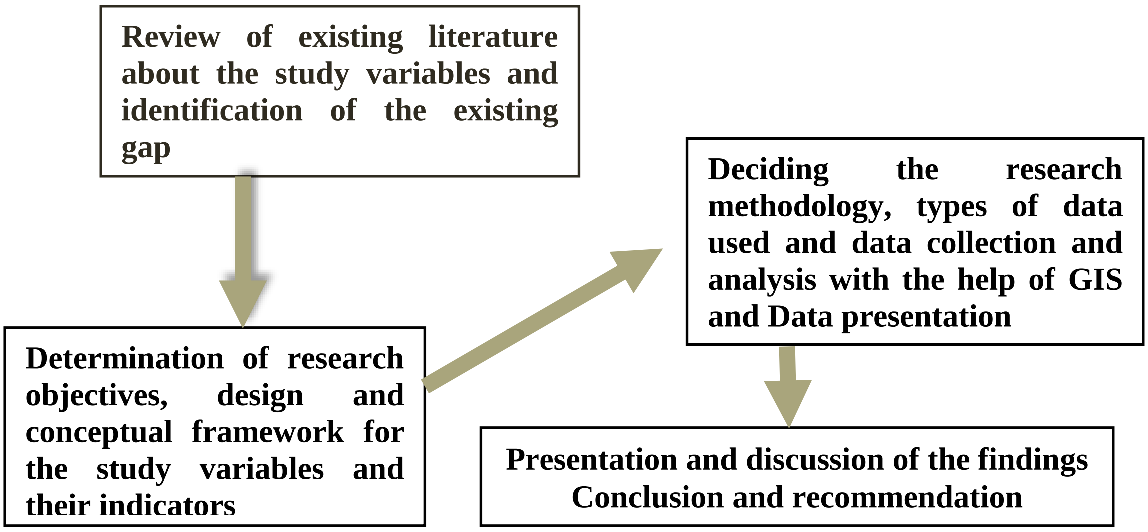

Figure 2.1: Methodology flowchart followed by the researcher

3. Results

3.1 Considered driving factors of flood vulnerability zones

The assessment of driving factors influencing flood vulnerability in Ngororero District reveals nine key factors: elevation, slope, Topographical Wetness Index (TWI), flow accumulation, proximity to rivers and roads, land use/land cover (LULC), soil properties, and rainfall. Understanding these factors provides a comprehensive insight into the causes of vulnerability, informing targeted mitigation strategies and enabling informed decision-making for disaster risk reduction and resilience-building efforts in the community.

4.1.1 Elevation

The elevation is a critical factor in determining the flood vulnerability mapping in any region. The elevation map revealed significant variation across the study area, with the lowest elevation recorded at 1397 m and the highest at 2889 m, as illustrated in Figure 4.1. Notably, the marginal eastern and southern parts exhibited lower elevations, indicative of potential flood-prone areas. Conversely, highly elevated areas were predominantly dispersed in the western region, highlighting their reduced susceptibility to flooding. Moreover, moderately elevated areas were spatially distributed towards the northern and central portions of the study area, presenting a varied topographical landscape with implications for flood vulnerability and risk assessment. This diverse elevation profile underscores the need for targeted measures to address the specific vulnerability dynamics within different elevation zones, contributing to a more nuanced understanding of flood vulnerability within Ngororero district.

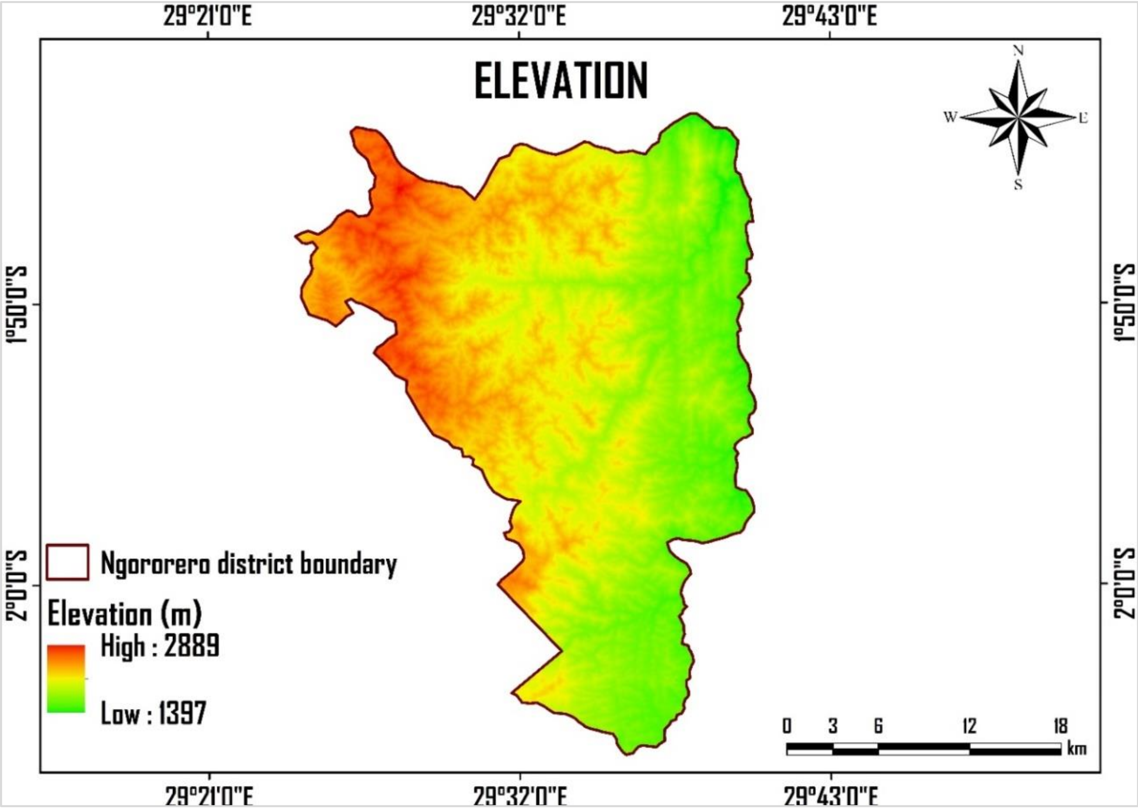

Figure 4.1: Thematic layer of elevation in meters

4.1.2 Slope

The assessment of slope within a study area plays a pivotal role in understanding flood vulnerability dynamics. The topographical characteristics, particularly slope, significantly influence the flow and accumulation of water during precipitation events, ultimately impacting the propensity for flooding. While high slopes can accelerate runoff and increase the risk of erosion and flash floods, low slopes may lead to water accumulation and prolonged inundation. In this study, the slope analysis revealed that the study area is predominantly characterized by high, steep slope gradients. In this study, the slope values ranged from 0 to 55 degrees (Figure 4.2), with the higher slopes making up the majority of the area. When categorized into two classes on the slope map, the class representing steeper slopes was far more spatially extensive compared to the class of lower slope areas. While pockets of lower slope zones were present, they represented relatively nominal and dispersed parts of the overall study area. Conversely, the steep high slope areas exhibited a more concentrated and contiguous distribution pattern. This prevalence of high slopes was particularly notable in the central region of the northern part, where steep gradients dominated the terrain. In summary, the slope characteristics of the study area were markedly skewed towards high, steeply graded topography rather than low, gentle slopes. The steep slopes were the predominant landscape feature, with lower slopes being comparatively limited in their spatial extent and distribution.

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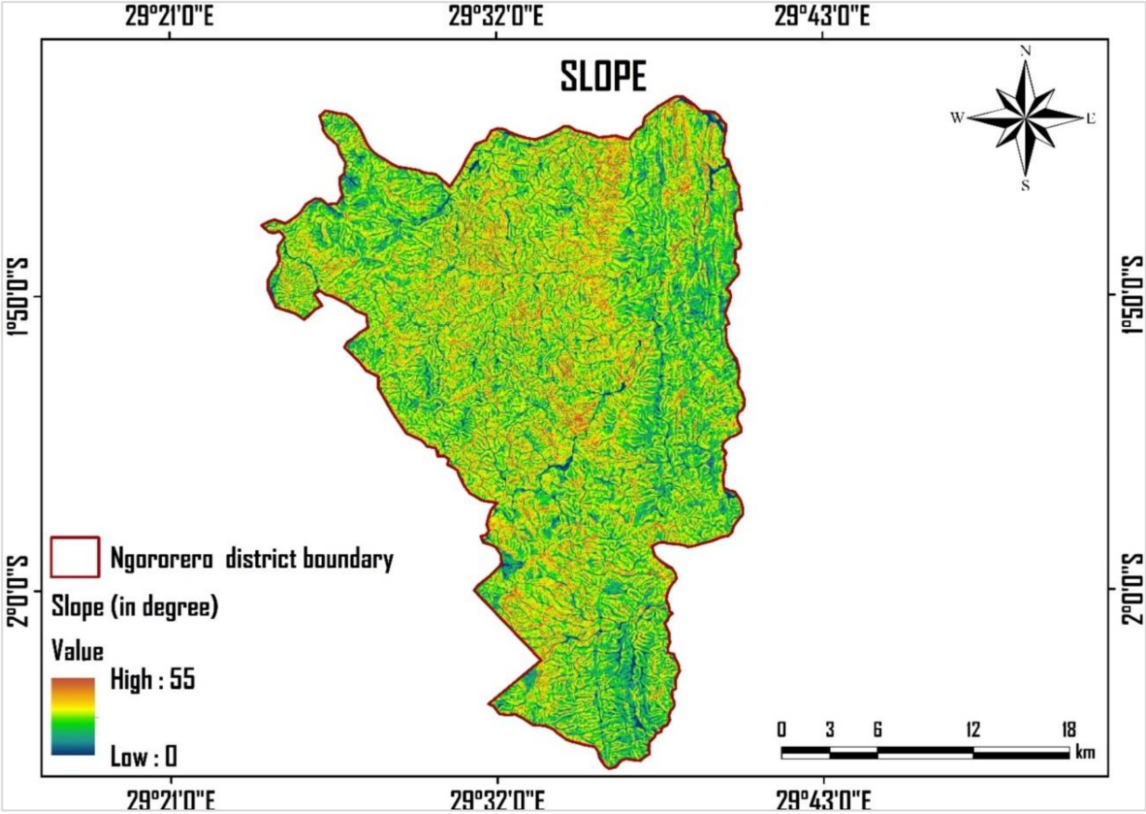

Figure 4.2: Thematic layer of slope (Degrees)

4.1.3 Topographic wetness index (TWI)

The Topographic Wetness Index (TWI) serves as a critical tool in flood vulnerability assessment by quantifying the relative wetness potential of an area based on its topography. TWI factors in slope and upstream contributing area to indicate areas prone to saturation and water accumulation, essential indicators in flood risk analysis. By delineating areas with high wetness potential, TWI assists in identifying regions susceptible to inundation, groundwater influence, and heightened flood risk. Understanding the role of TWI in flood vulnerability assessment enables targeted interventions and risk management strategies to mitigate the impact of floods effectively. In this study, the topographic wetness index (TWI) analysis across the study area revealed a dominance of lower TWI values, indicating an overall higher possibility of flooding throughout the region. The calculated TWI ranged from 2.34 to 22.52 (Figure 4.3), with the lower end of this spectrum being more widely represented spatially. Areas with lower TWI values correspond to a decreasing rate of soil moisture and higher runoff potential, thereby accelerating the possibility of flooding events. Conversely, higher TWI values suggest decreased flooding likelihood due to greater moisture retention and drainage. In the context of the study area, the spatial distribution pattern was skewed towards these lower TWI ranges that represent higher flood potential. While some isolated pockets of higher TWI existed, suggesting localized zones of better drainage, the landscape was predominantly characterized by topographic and soil drainage conditions that increase runoff and flood risk based on the TWI mapping. This distribution indicates that flood mitigation and runoff management strategies may be particularly crucial across large swaths of the study area, as the terrain favors moisture accumulation and runoff generation according to the calculated TWI values and their relation to flooding dynamics.

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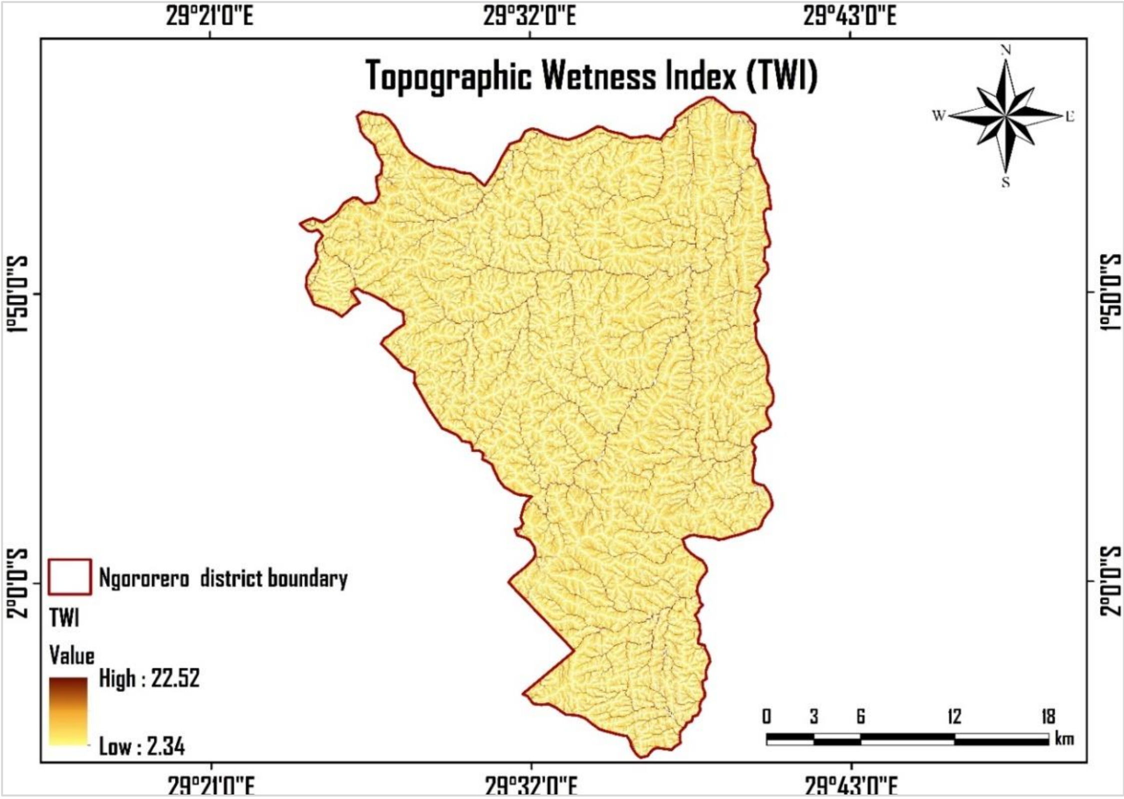

Figure 4.3: Thematic layer of Tropical Wetness Index (TWI)

4.1.4 Flow accumulation

Flow accumulation is a critical component in flood vulnerability assessment, providing insights into the potential pathways water may take during heavy precipitation events. By mapping the accumulation of flow across a terrain, important patterns of water movement and concentration can be identified, aiding in the assessment of flood risk areas. Understanding flow accumulation helps in predicting flood extents, identifying flood-prone zones. In this study, the flow accumulation analysis (Figure 4.4) delineated the drainage patterns and runoff concentration zones that govern flooding dynamics across the study area. Notably, the results exhibited several riverine networks dispersed throughout the region, which serve as pivotal conduits for accumulated runoff during precipitation events. The flow accumulation values were classified into two subgroups - high and low accumulation zones. These classes indicate the zones which effectively highlighted the river channels and their immediate floodplains, where upslope surface runoff converges, significantly elevating the volume of water that must be conveyed downstream. During heavy rainfall periods, these high accumulation river corridors are highly vulnerable to overbank flooding and inundation of the surrounding low-lying areas. The concentrated runoff from upslope basins can rapidly overwhelm the carrying capacities of the rivers, leading to widespread flooding impacts along their paths. In contrast, the zones of relatively low or negligible flow accumulation away from the riverine networks may still experience localized runoff, they are comparatively less vulnerable to large-scale flooding directly caused by swelling rivers during extreme precipitation events. Areas in close proximity to rivers, particularly along their middle and lower reaches where accumulation peaks, are frequently identified as high-vulnerable zones for riverine flooding when runoff volumes exceed channel capacities. Consequently, the flow accumulation mapping provides critical insights into prioritizing flood mitigation strategies, such as structural flood control measures, riparian zone management, and land use policies focused on these high accumulation river corridors to reduce the vulnerability of communities and infrastructure within the flood-prone areas.

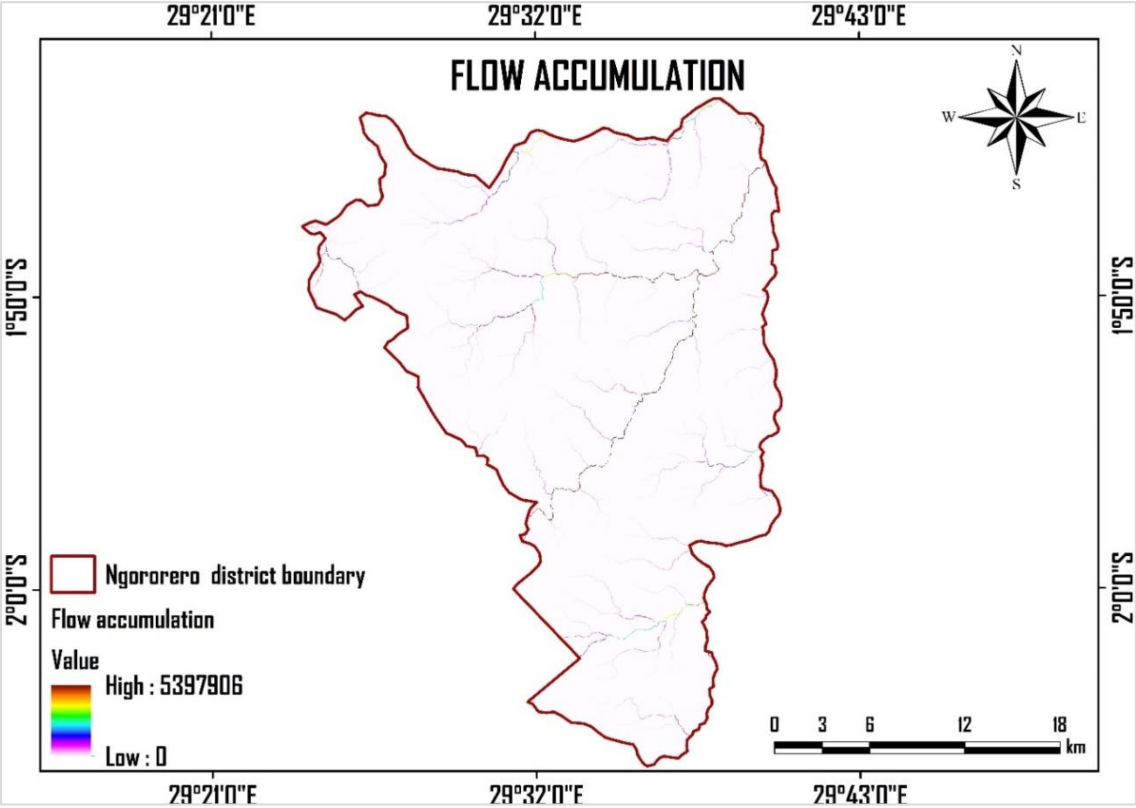

Figure 4.4: Thematic layer of flow accumulation

4.1.5 Proximity to rivers

The proximity to rivers plays a vital role in flood vulnerability assessment as it directly influences the susceptibility of an area to flooding events. Areas located in close proximity to rivers are inherently at a higher risk of flooding due to the potential for river overflow during heavy rainfall. Proximity to rivers emerged as a crucial conditioning factor influencing flood vulnerability across the study area. The analysis revealed that the vast majority of the region lies within close proximity to riverine networks (Figure 4.5), with distances ranging from less than 100 meters to over 400 meters. Areas situated at lower distance values especially toward the western and southern part, particularly those less than 100 meters from rivers, exhibited heightened exposure to potential flooding events. The concentration of the study area's landscape near river channels, with most locations falling within the less than 100-meter range, suggests a significant portion of the region is highly vulnerable to riverine flooding impacts. When heavy precipitation occurs, these proximal areas are directly exposed to rapid inundation as water levels in the rivers rise and overtop their banks. Conversely, the relatively areas situated beyond the 400-meter threshold from rivers represent zones with lower inherent vulnerability to riverine flooding under typical conditions. However, it's important to note that exceptionally severe flood events or compounding factors like poor drainage or impervious surfaces can still pose residual risks in these distant areas. The dominance of short proximity values highlights the need for focused flood mitigation efforts, such as structural protection measures like levees or floodwalls, effective early warning systems, and land use policies that limit development in these high-exposure zones adjacent to rivers. Additionally, maintaining the integrity of riparian buffers and implementing sustainable drainage strategies can help mitigate flood risks in the river-proximal areas that constitute the majority of the study region.

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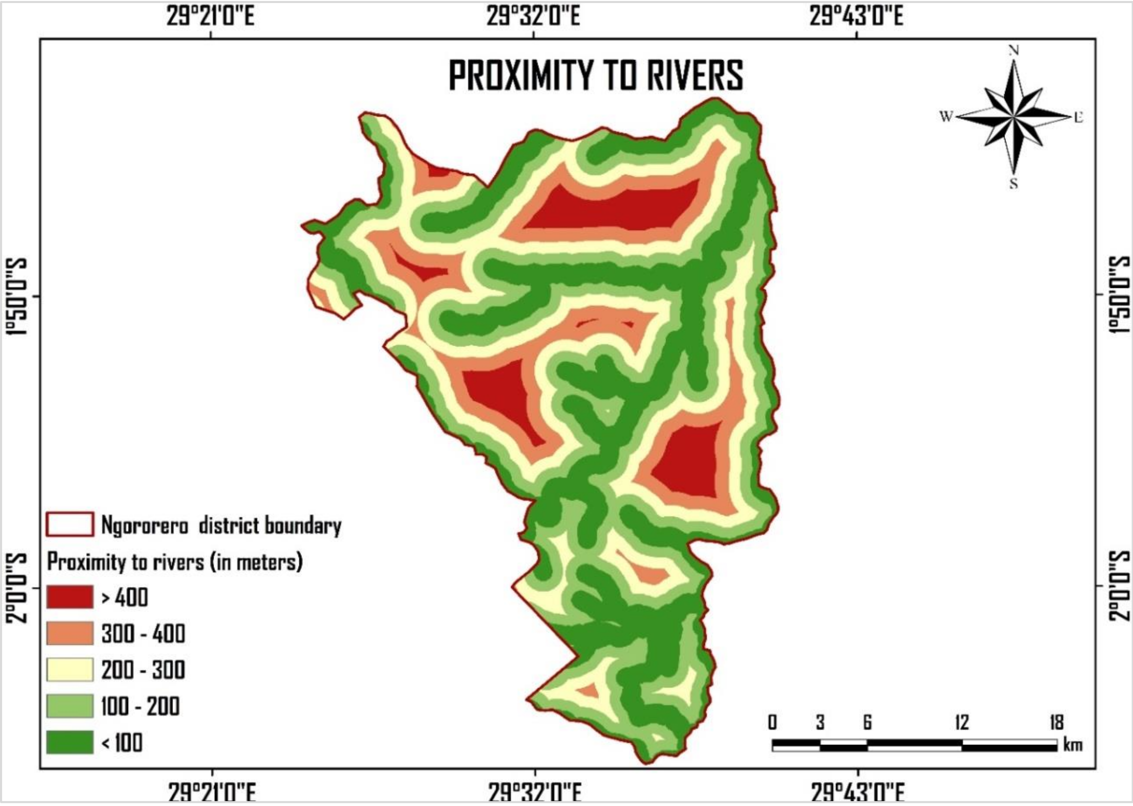

Figure 4.5: Thematic layer of proximity to the rivers

4.1.6 Proximity to roads

The proximity to roads plays a significant role in flood vulnerability assessment as it impacts the accessibility of areas potentially affected by flooding events. Roads serve as critical infrastructure for evacuation, emergency response, and the transportation of essential goods and services during and after flood events. Understanding the spatial relationship between roads and flood-prone areas is crucial for assessing flood risk, planning evacuation routes, and implementing effective disaster management strategies. Hence, proximity to road networks emerged as a pivotal factor influencing flood vulnerability across the study area. This factor's significance stems from the ability of roads to impede rainwater infiltration and exacerbate runoff concentration, thereby increasing flood risk in surrounding vicinities. The proximity analysis classified the study area into five distance classes ranging from less than 100m to greater than 400m away from roads. Areas in close proximity, falling within the <100m range (Figure 4.6), were predominantly observed in the eastern, western, and southern parts of the region. These zones exhibited the highest vulnerability to flooding events based on their proximity to roads. Extensive research has demonstrated that impervious road surfaces and associated drainage infrastructure can significantly disrupt natural water infiltration processes during heavy rainfall episodes. The resulting rapid runoff accumulation, combined with obstructions to flow paths, elevates the propensity for inundation in adjacent areas, particularly those in the immediate road vicinities represented by the lowest distance class. However, it's crucial to note that flood vulnerability is a multifaceted phenomenon influenced by a confluence of factors beyond just proximity to roads. Terrain characteristics, soil conditions, land use patterns, and the presence of other hydrological features can further modulate or exacerbate flood risk even in areas more distant from road networks.

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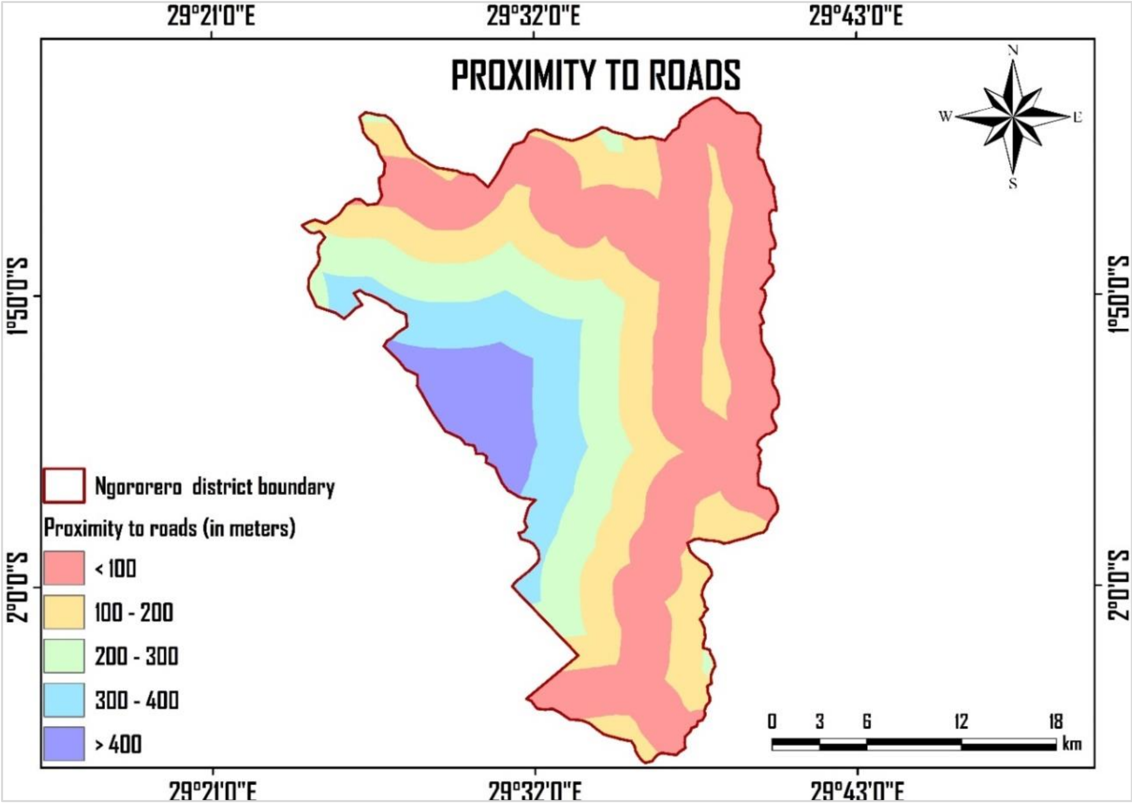

Figure 4.6: Thematic layer of proximity to the roads (in meters)

4.1.7 Land Use Land Cover (LULC)

The analysis of Land Use and Land Cover (LULC) is instrumental in flood vulnerability assessment as it provides critical insights into the spatial distribution of various land-use types, and ecosystems that directly influence the susceptibility of an area to flooding events. Understanding how human activities and natural features interact within the landscape is crucial for assessing flood risk, identifying areas vulnerable to inundation, and implementing effective mitigation strategies. LULC assessment enables the identification of areas that may exacerbate or buffer against flooding, guiding land use planning, and sustainable development practices to enhance resilience in the face of potential flooding incidents. Hence, LULC patterns emerged as a critical determinant of flood vulnerability across the study area. The LULC mapping revealed six distinct categories: forestland, grassland, cropland, built-up areas, wetlands, and water bodies (Figure 4.7), each exerting varying degrees of influence on surface runoff dynamics and flood susceptibility. Notably, the study area was predominantly occupied by croplands, constituting a significant portion of the landscape. This prevalence of agricultural lands heightens the vulnerability of crop yields and agricultural livelihoods to potential flood impacts. Additionally, built-up areas were observed to be evenly dispersed throughout the study region. These possible impervious surfaces inhibit natural infiltration processes, leading to increased surface runoff and elevated flood risk within and around urban clusters. The distribution of built-up zones across the study area underscores the vulnerability of communities and infrastructure to flooding events. In contrast, areas with substantial vegetation cover, such as forestlands and grasslands, normally exhibit lower inherent flood vulnerability. These natural landscapes facilitate rainwater infiltration and attenuate runoff velocities, thereby mitigating flood potentials. However, it's important to note that in this study, vegetated areas can experience flooding if rainfall intensities exceed soil infiltration capacities or if runoff from adjacent impervious surfaces

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accumulates in these zones. The western part of the study area stood out as being comparatively less vegetated, suggesting a heightened vulnerability to flooding in these regions. Lack of adequate vegetation cover can exacerbate runoff generation and impede natural drainage. Consequently, the LULC mapping highlights the need for integrated flood management strategies that balance urban development with sustainable land use practices.

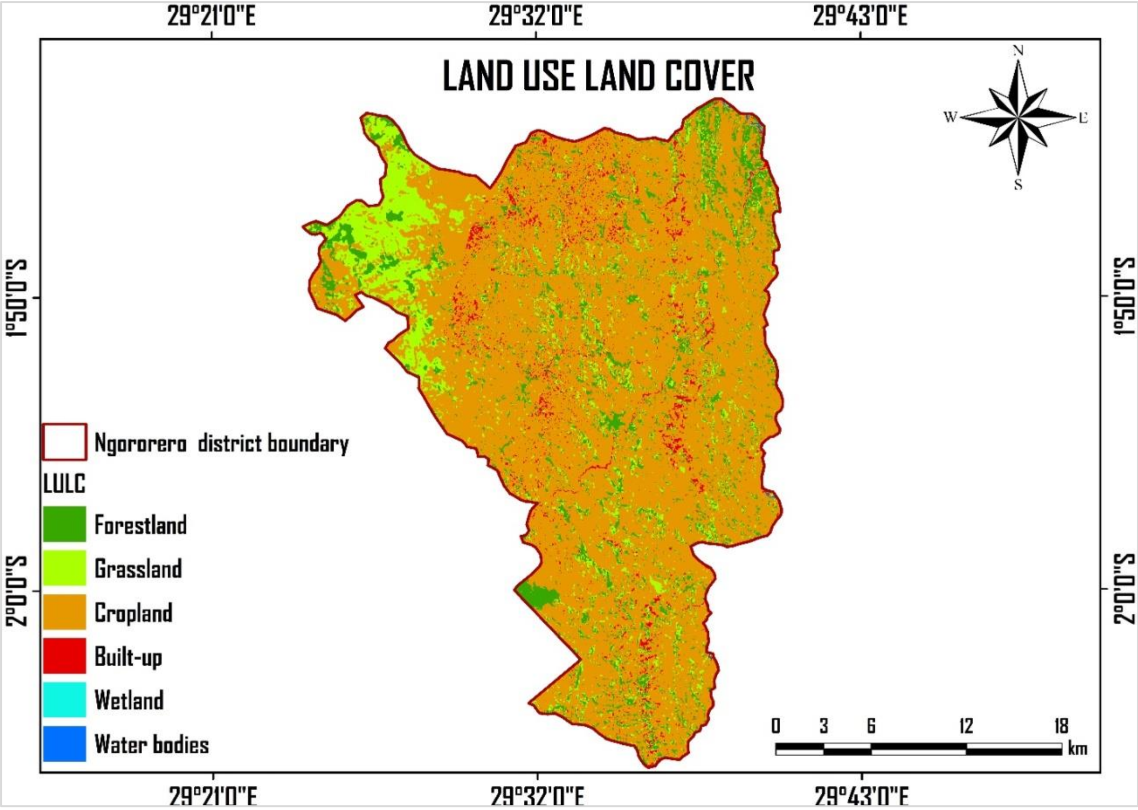

Figure 4.7: Thematic layer of land use land cover

4.1.8 Soil texture

Soil texture is a critical factor in flood vulnerability assessment as it influences the infiltration and retention of water within the landscape. The composition and structure of soil directly impact the potential for water saturation and runoff, thereby affecting the susceptibility of an area to flooding events. Understanding the soil texture provides valuable insights into the capacity of the land to absorb and convey water, guiding assessments of flood risk, planning land use, and implementing effective mitigation strategies. Hence, soil texture emerged as a crucial topographic factor influencing flood dynamics and vulnerability patterns within the study area. The soil characteristics directly impact water flow directions, runoff generation, and soil moisture retention during flooding events, thereby modulating flood risks across different regions. In this study, the soil texture analysis revealed the presence of four distinct classes: sandy-clay-loam, clay loam, sandy clay, and clay (Figure 4.8). Among these, the clay loam texture was the most dominant, exhibiting a widespread distribution across all parts of the study area. The prevalence of clay loam soils is particularly noteworthy from a flood vulnerability perspective. Numerous previous studies have highlighted the propensity of clay loam soils to impede infiltration and exacerbate surface runoff during heavy rainfall or flooding scenarios. This soil texture's low permeability and high water-holding capacity can lead to rapid saturation, thus increasing the likelihood of overland flow and inundation in areas dominated by clay loam compositions. Additionally, the clay soil was observed across

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the study area, particularly toward the southern and north-eastern parts. However, their flood vulnerability can still be influenced by other factors such as slope, vegetation cover, and the intensity of precipitation events. The spatial distribution of soil textures across the study area underscores the need for targeted flood mitigation strategies tailored to the specific soil characteristics of each region. Areas dominated by clay loam soils may require enhanced drainage infrastructure, sustainable urban drainage systems, and land use policies that promote soil conservation and permeability.

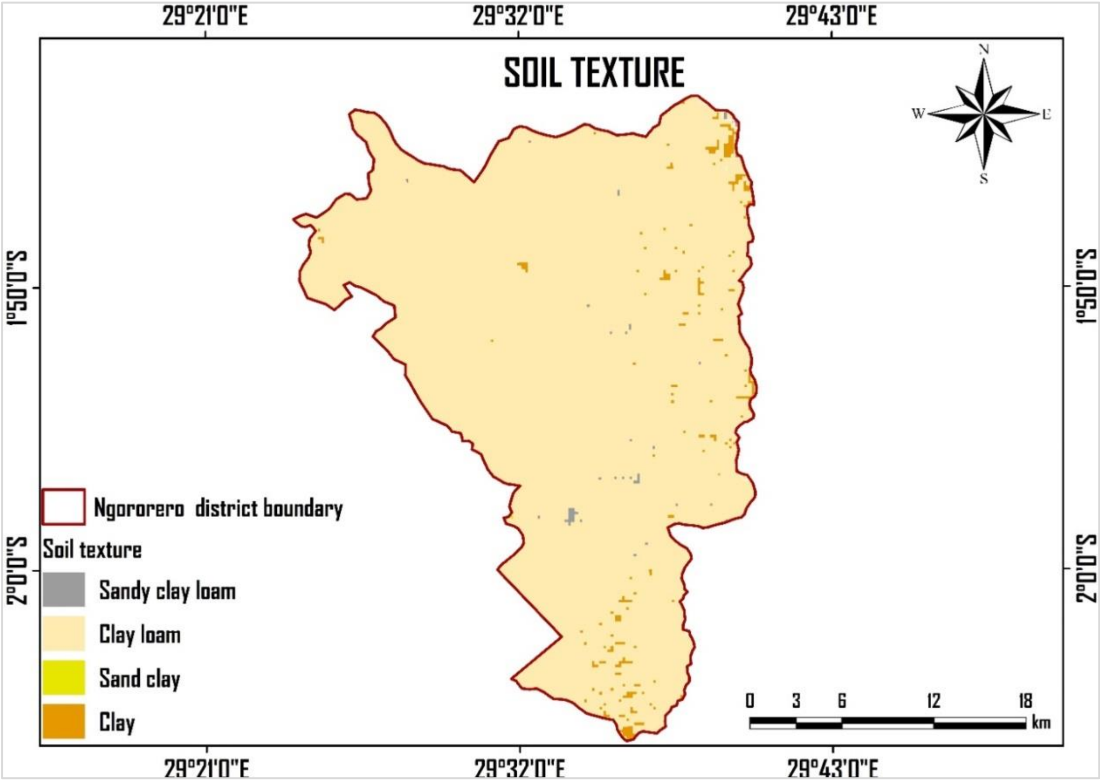

Figure 4.8: Thematic layer of soil texture

4.1.9 Rainfall

Among the various factors contributing to flood vulnerability, rainfall emerged as the most significant climatic determinant across the study area. The rainfall analysis classified the region into two distinct classes, ranging from 1127 mm to 1292 mm of annual precipitation (Figure 4.9). A pronounced spatial gradient was observed, with rainfall amounts progressively increasing from the eastern parts towards the western sections of the study area. This pattern contrasted with the distribution of vegetation cover, as the western regions exhibited higher forestland and grassland coverage compared to the eastern parts. Crucially, the western portions of the study area experienced higher mean annual rainfall despite being more vegetated. Numerous studies have consistently highlighted rainfall as the primary driver of flooding events, as elevated precipitation levels, particularly intense or prolonged rainfall episodes, can overwhelm natural and artificial drainage systems, leading to surface runoff generation, soil saturation, and consequent inundation. While the eastern parts of the study area received comparatively lower mean annual rainfall, it is essential to recognize that flood vulnerability is a complex phenomenon influenced by the interplay of multiple factors. Even in areas with lower annual rainfall, the presence of impervious surfaces, inadequate drainage infrastructure, or intense localized precipitation events can still trigger flooding incidents.

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However, the spatial distribution of mean annual rainfall serves as a critical indicator for assessing and prioritizing flood mitigation strategies within the study area.

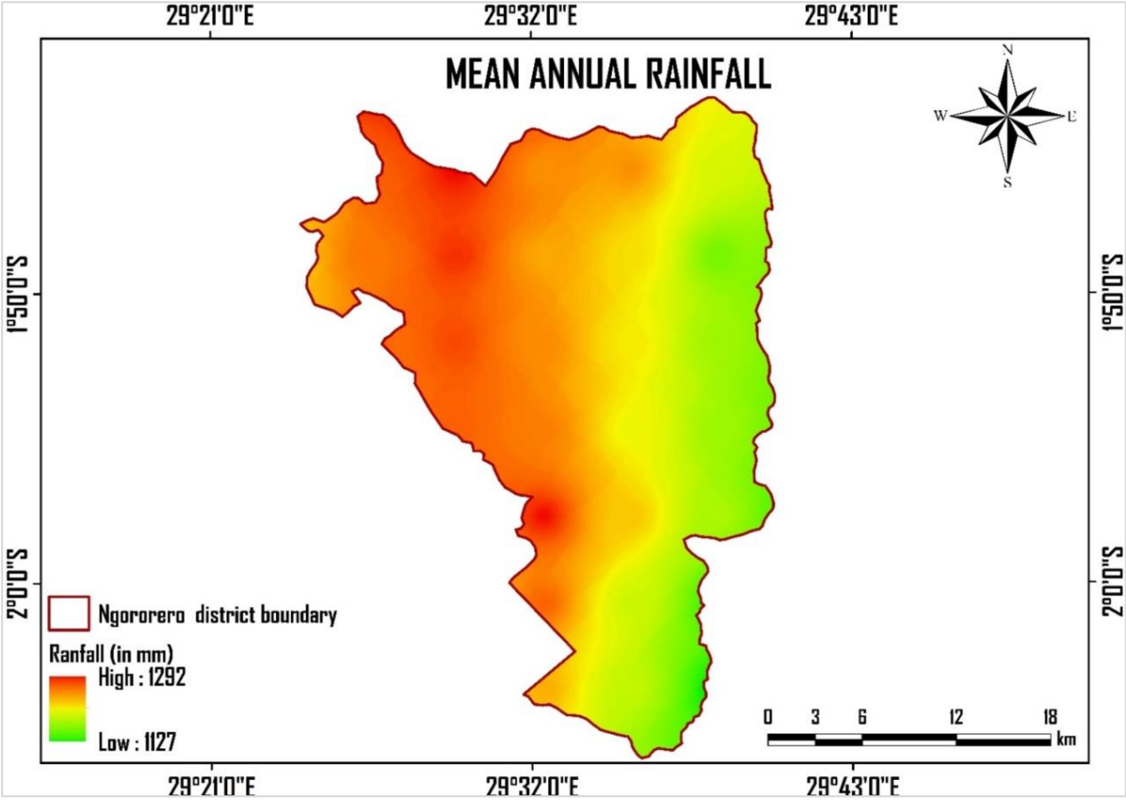

Figure 4.9: Thematic layer of rainfall (in mm)

4.2 Flood vulnerable zones in Ngororero district

The most important aspect in developing flood vulnerability map is to precisely identify the areas that can have floods in the future. In this study, a flood vulnerability map was prepared by incorporating the 9 flood influencing layers. The obtained vulnerability map was classified into five groups: very high, high, moderate, low, and very low flood venerable zones in Ngororero District.

The flood vulnerability assessment revealed a heterogeneous distribution of vulnerability zones across the study area (Figure 4.10), underscoring the complex interplay of multiple driving factors in modulating flood vulnerability. The very high and high vulnerability areas collectively occupied a substantial portion of the district, with a noticeable concentration in the north-western and northern regions. These zones exhibited a confluence of conditions that exacerbated flood risks, such as high rainfall amounts (Figure 4.9), impervious surfaces from LULC, and proximity to major river networks. The prevalence of flood-prone soils, particularly clay loam, further compounded the vulnerability in these areas, highlighting the influence of soil characteristics on water infiltration and runoff generation. While the very high vulnerability zones occupied 12.4% of the total area (Figure 4.12) the high vulnerability zones constituted a significant 54.2%, indicating a widespread presence of vulnerability factors across the district. These regions likely shared similar traits to the very high vulnerability areas, albeit with a slightly less severe interplay of contributing factors. In contrast, the moderately vulnerable areas, comprising 18.1% of the study area, were predominantly concentrated towards the southern and central parts of the district. These zones may have benefited from a combination of factors that mitigated the overall flood risk,

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such as better drainage conditions, lower rainfall amounts, or the presence of more permeable soil types (Figure 4.8).

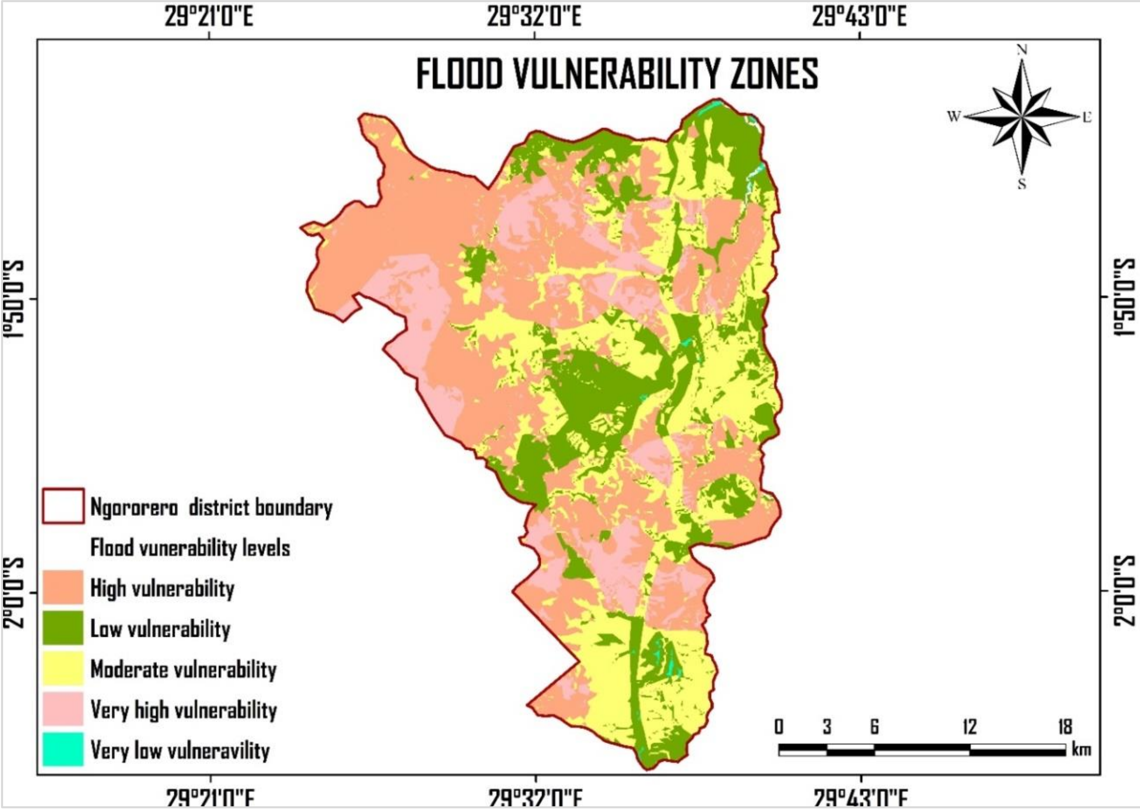

Figure 4.10: Spatial distribution of flood vulnerability zones in Ngororero district

However, localized factors like urban development or topographic depressions could still contribute to moderate flood vulnerability in these regions. The low vulnerability zones, constituting 14.1% of the total area, were primarily localized towards the central parts of the study area, extending westward and also towards the north-eastern regions. These areas exhibited characteristics that significantly reduced their flood vulnerability, such as lower rainfall intensities, well-drained soils, moderate elevations (Figure 4.1), greater distances from rivers and roads (Figure 4 and 5). Nevertheless, it's important to note that even low vulnerability areas may still experience flooding under extreme precipitation events or when multiple vulnerability factors converge. Finally, the very low vulnerability areas represented a relatively small portion of the study area at 1.2% and were scattered across various locations. These zones likely possessed a favourable combination of factors that minimized flood risks, including vegetated landscapes (Figure 4.7), highly permeable soils, significant distances from water bodies and urban areas, and relatively low rainfall amounts. It's crucial to recognize that flood vulnerability is a dynamic phenomenon influenced by the intricate interplay of multiple natural and anthropogenic factors. While the vulnerability zoning provides valuable insights for risk assessment and mitigation planning, it's essential to continuously monitor changes in these contributing factors and adapt strategies accordingly.

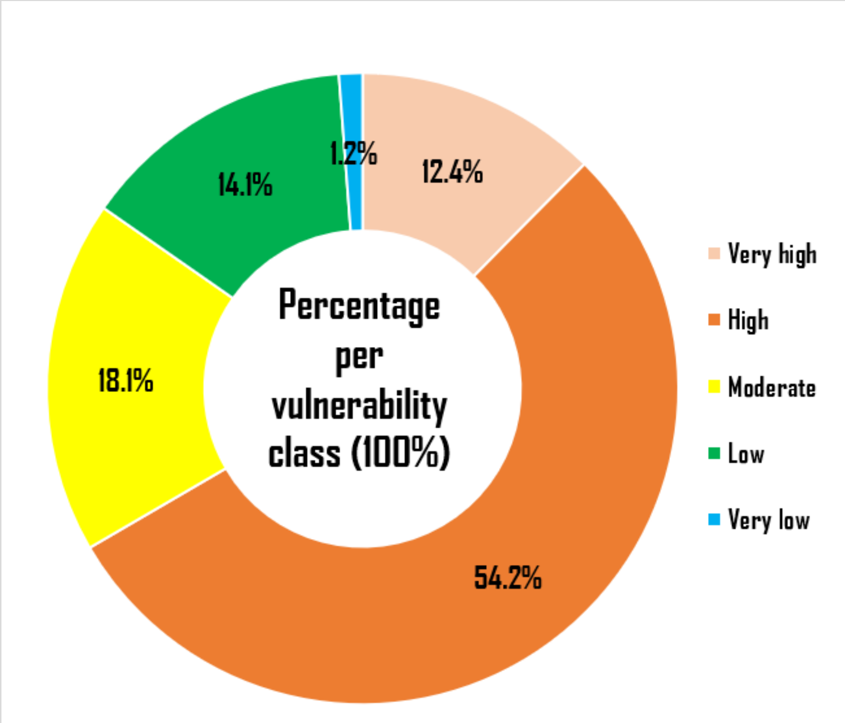

Figure 4. 11: Percentage per each classified vulnerability class in the study area

4.3 The main influencing factors of flood vulnerability zones in Ngororero district

The table 4.1 presents an in-depth analysis of factors influencing flood vulnerability in Ngororero District, categorizing their contribution levels into high, moderate, and low influence based on calculated weight percentages derived from the Analytical Hierarchy Process (AHP). Among these factors, rainfall emerges as the most significant contributor, with a weight of 26.7%, highlighting its pivotal role in exacerbating flood risk. Proximity to rivers follows closely with a weight of 21.4%, indicating its crucial influence on flood vulnerability. Flow accumulation, with a weight of 13.3%, is another critical factor determining flood vulnerability, emphasizing the importance of managing high-flow accumulation zones effectively. Additionally, land use and land cover (LULC) patterns, accounting for 12.5%, significantly contribute to flood vulnerability, underlining the impact of land utilization on hydrological responses to rainfall.

Moreover, soil texture and elevation exhibit moderate levels of contribution to flood vulnerability, with weights of 9.4% and 8.2%, respectively. Soil texture influences water-holding capacity and infiltration rates, while elevation affects the vulnerability of lower-lying areas to flooding. These factors play crucial roles in determining flood risk and inform targeted mitigation strategies.

Conversely, factors such as topographical wetness index (TWI), proximity to roads, and slope exhibit low levels of contribution to flood vulnerability, with weights of 4.1%, 2.8%, and 1.6%, respectively. While TWI provides insights into potential flood-prone areas, proximity to roads underscores the impact of infrastructure on flood vulnerability. Slope, albeit minor, influences water flow patterns and erosion potential, requiring consideration in conjunction with other factors for a comprehensive understanding of flood risk.

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Table 4.1: Influencing factors per level of contribution to flood vulnerability with their calculated weight using AHP

N0	Influencing factor	Weight (%)	Position	Level of contribution
1	Elevation	8.2	6	Moderate influence
2	Slope	1.6	9	Low influence
3	Flow accumulation	13.3	3	High influence
4	TWI	4.1	7	Low influence
5	Proximity to rivers	21.4	2	High influence
6	Proximity to roads	2.8	8	Low influence
7	LULC	12.5	4	High influence
8	Soil texture	9.4	5	Moderate influence
9	Rainfall	26.7	1	High influence

4.4 Existing and suggested flood mitigation measures for community-based flood resilience

In Ngororero District, flood vulnerability necessitates a multi-faceted approach to mitigation and resilience-building. Existing measures like tree planting, terracing, and dam construction address surface runoff and river flow, yet more sustainable land management practices, including afforestation and agroforestry, are needed to mitigate erosion and stabilize slopes. Natural water retention features such as wetlands and retention ponds, alongside resilient infrastructure upgrades and nature-based solutions, further enhance flood control. Community-based early warning systems, disaster preparedness training, and strengthened governance mechanisms contribute to community readiness and effective flood risk management. Education campaigns and incentives for resilient construction practices foster a culture of resilience. A comprehensive strategy integrating structural and non-structural measures tailored to local contexts is essential for enhancing flood resilience in Ngororero District, Rwanda.

4.5 Discussion of results

The research on flood vulnerability in Ngororero District identified specific areas at higher risk of inundation, offering insights crucial for targeted interventions. It analyzed key factors like rainfall, proximity to rivers, and land use, providing a nuanced understanding of flood susceptibility. The study evaluated existing mitigation measures and proposed tailored strategies for enhancing community resilience, aligning with previous works on flood vulnerability assessment and resilience planning. While studies by Xu et al. (2023) and Leta and Adugna (2023) emphasize analytical methods and community engagement, Yang et al. (2021) focused on regional resilience in China. Contrary to studies by Chisty et al. (2022) and Isia et al. (2023), which highlighted gender disparities and vulnerability dimensions, respectively, our research delved into specific influencing factors in the Ngororero context. In addition, our study extends beyond susceptibility mapping, integrating ecosystem-based solutions and community engagement for effective resilience planning. Complementing prior works by Mind'je et al. (2019, 2023) and Hirwa et al. (2023), our research provides practical insights tailored to the unique vulnerabilities of Ngororero District. By contextualizing findings with identified objectives, the study establishes a robust foundation for evidence-based decision-making, contributing to proactive flood risk reduction and community resilience enhancement in Rwanda.

4. Conclusion

In conclusion, the study on flood vulnerability in Ngororero District revealed crucial insights into the region's vulnerability to flooding and provided evidence-based recommendations for enhancing resilience. Through the analysis of driving factors along with the assessment of influencing factors using the Analytical Hierarchy Process (AHP), the study identified key areas of vulnerability and prioritized interventions. Additionally, the discussion on existing and suggested flood mitigation measures underscored the importance of ecosystem-based solutions, resilient infrastructure, and community engagement in disaster preparedness. By implementing these strategies, communities can mitigate the adverse impacts of flooding, safeguarding lives, livelihoods, and ecosystems. Ultimately, the study emphasizes the importance of proactive measures and collaborative efforts to build resilience and adapt to the challenges posed by floods in Ngororero District, Rwanda.

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